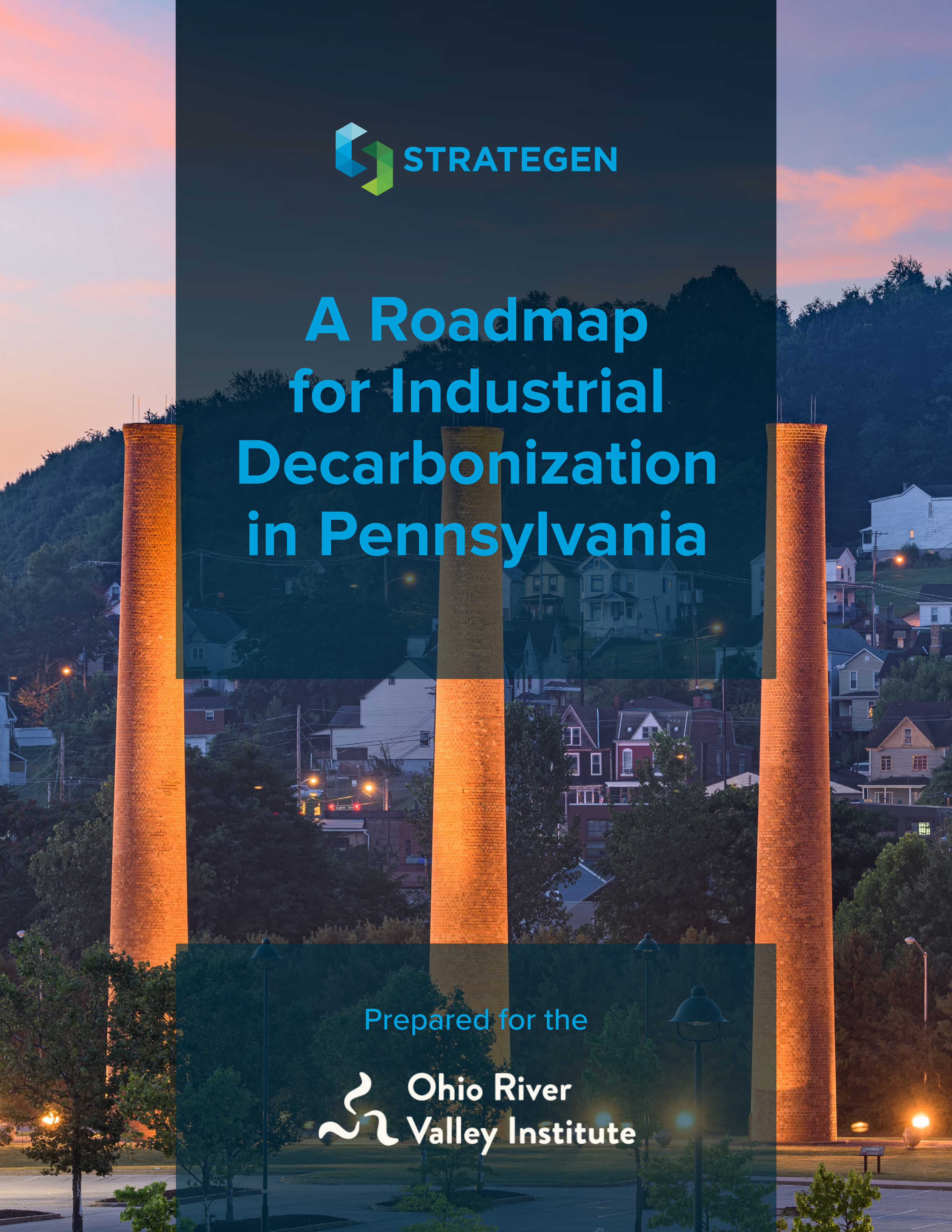

STRATEGEN

A Roadmap for Industrial Decarbonization in Pennsylvania

Prepared for the

Ohio River Valley Institute

About the Ohio River Valley Institute

The Ohio River Valley Institute is an independent, nonprofit research and communications center — a think tank — founded in 2020. We equip the region's residents and decision-makers with the policy research and practical tools they need to chart a course toward shared prosperity, clean energy, and more equitable civic structures. Our work includes in-depth research, commentary, and analysis, delivered online, by email, and in-person to policy champions, emerging leaders, and a range of community partners.

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This document is prepared by Strategen Consulting, Inc. for the Ohio River Valley Institute.

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Executive Summary

Across the United States, progress is accelerating toward economy-wide decarbonization. The establishment of federal emissions reduction targets, coupled with the passage of major pieces of legislation to advance decarbonization, mark historic steps toward addressing climate change. Still, significant hurdles remain to meeting both near-term and mid-century climate goals. These obstacles are particularly acute in the industrial sector. Compared to other economic sectors, such as power or buildings, industry is conventionally considered "difficult to decarbonize," and progress toward decarbonization has been accordingly slower. The challenges in decarbonizing the industrial sector stem from a range of factors, including the diversity of industrial processes, the need for high temperature heat to drive many processes, greenhouse gas (GHG) emissions released as byproducts of industrial processes, and growing demand for many industrial products.

In Pennsylvania, the industrial sector has been a central economic driver for more than a century, producing critical goods, including steel, cement, and glass, that helped build and grow the modern U.S. economy. Today, manufacturing contributes more than $113 billion in state domestic product and provides 11% of the commonwealth's jobs.[1] This significant manufacturing footprint means that industry is responsible for one-third of Pennsylvania's GHG emissions, the largest-emitting sector in the commonwealth's economy. While state policies, research and demonstration projects, and other ongoing efforts will help move Pennsylvania toward its goal of reducing economy-wide GHG emissions 80% below 2005 levels by 2050, emissions from the industrial sector are still projected to increase in the future, absent further actions.

To chart a path toward Pennsylvania's goals, Strategen developed an industrial decarbonization roadmap through 2050. This pathway addresses emissions from all industrial subsectors, including fossil fuel extraction and delivery, iron and steel, minerals (e.g., cement, lime), chemicals, and refining, among others. To address emissions from these sectors, the roadmap explores the role of five major decarbonization levers: energy efficiency, material efficiency, electrification, fuel switching, and carbon capture and storage. In some circumstances, production ramp-downs and facility and equipment retirements have also been considered. Pursuing the decarbonization pathways outlined in this report would reduce carbon dioxide equivalent (CO_2e) emissions from 2019 baseline levels by 18.2 million metric tons (MMT) by 2030 and 72.6 MMT by 2050, resulting in an 84% reduction (*see Figure 1*). Across all subsectors, transitioning from fossil fuel combustion to electrification enables roughly half of the total emissions reductions, followed by efficiency, carbon capture, and fuel switching.

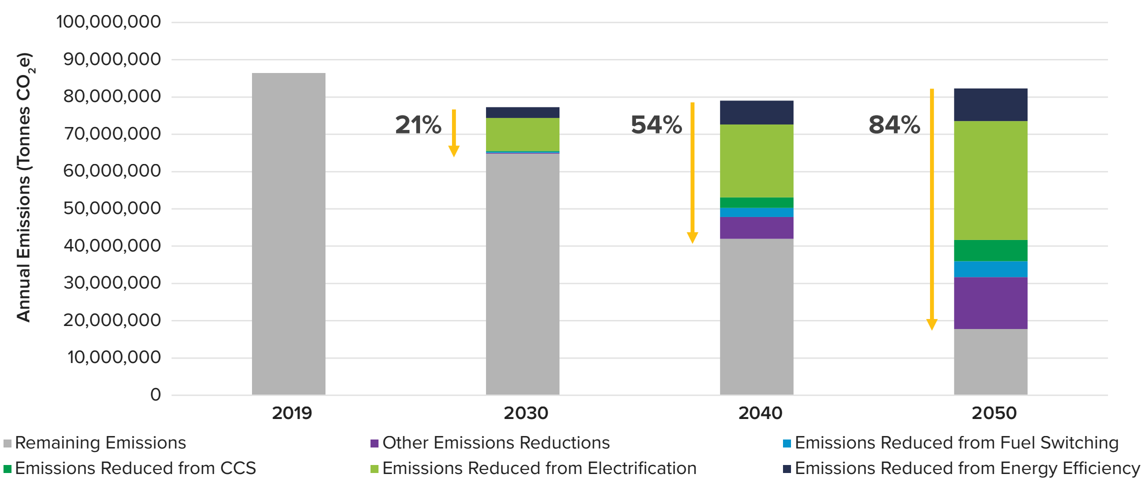


FIGURE 1: Pennsylvania Industrial Decarbonization Pathway, by decarbonization lever

1 Bureau of Labor Statistics, "The Economics Daily: A Look at Manufacturing Jobs on National Manufacturing Day," October 6, 2023. https://www.bls.gov/opub/ted/2023/a-look-at-manufacturing-jobs-on-national-manufacturing-day.htm.

As shown in *Figure 2*, the subsectors contributing the most to overall emissions reductions are fossil fuel extraction and delivery, low heat subsectors, and metals, which includes iron and steel.

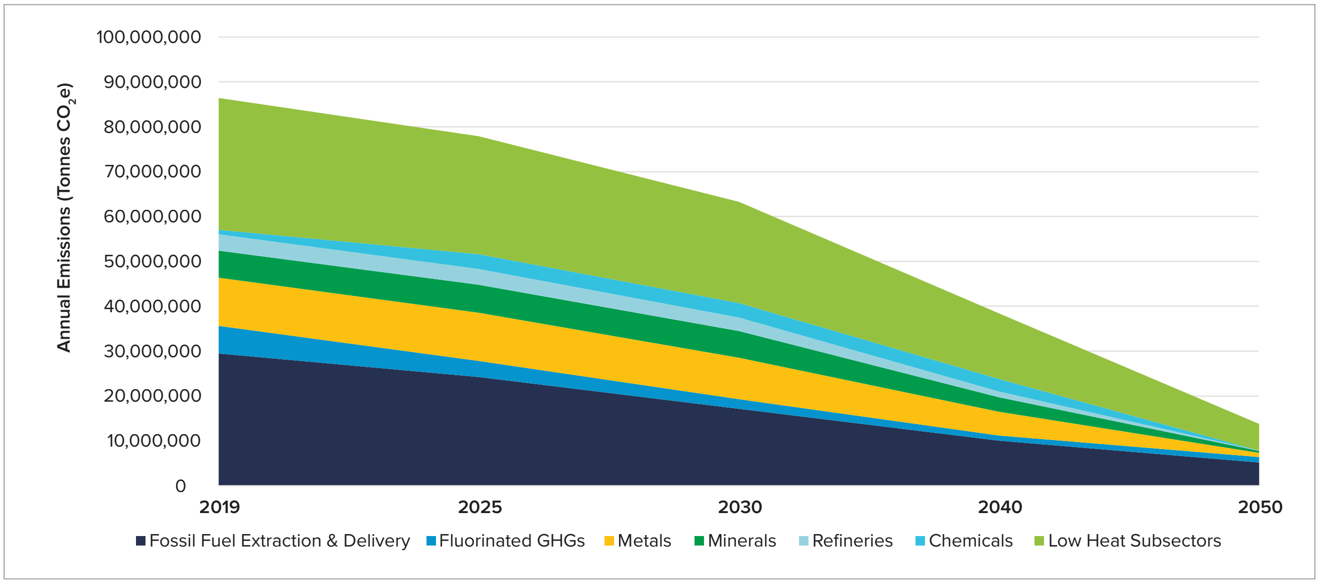


FIGURE 2: Pennsylvania Industrial Decarbonization Pathway, by industrial subsector

Strategen's roadmap would require $34.6 billion in unsubsidized implementation expenditures across all subsectors by 2050; incorporating federal tax credits for carbon capture lowers the cost to $33.7 billion. While this is a massive investment, it would also result in significant societal benefits through avoided GHG emissions, reaching $14 billion in savings annually by 2050, compared to a business-as-usual scenario. This decarbonization pathway also offers the potential for major health and equity improvements in Pennsylvania by sharply reducing the emission of local pollutants from fossil fuel usage in the industrial sector, which have a disproportionate impact on fenceline communities. Industrial decarbonization can be a local economic driver as well, while serving to maintain the competitiveness of Pennsylvania industries in global and national economies that are increasingly factoring environmental and sustainability attributes into the marketplace.

Successfully decarbonizing Pennsylvania's industrial sector, while achieving the potential benefits outlined above, necessitates proactive measures by both state government and industry. The following complementary actions can enable and accelerate progress toward decarbonization:

+ Maximize energy efficiency investments in industry to reduce the need for more costly decarbonization solutions.
+ Accelerate the decarbonization of Pennsylvania's power sector to enable economy-wide emissions reductions.
+ Explore options for an economy-wide carbon pricing mechanism, drawing on examples from other states.
+ Continue to detail strategies to decarbonize Pennsylvania's industrial sector in the next Climate Action Plan based on lessons learned from other states.
+ Evaluate and take advantage of federal funding opportunities and incentives for technologies that are expected to become cost effective and sustainable at scale.
+ Pursue community and worker engagement, and benefits planning for decarbonization projects and policies.
+ Invest in training and job placement programs that can develop new workers and channel existing skillsets to growth industries.
+ Explore options for state procurement of low-carbon industrial products to foster demand and in-state economic growth.

While decarbonizing Pennsylvania's industrial sector will be no small task, doing so will be critical to achieving both state and national climate targets. The commonwealth, as well as the communities and companies within it, all stand to gain significantly from proactive investments in industrial decarbonization.

Introduction

This report lays out a roadmap to decarbonize Pennsylvania's industrial sector, a critical step on the path to both statewide and nationwide decarbonization. The *Introduction* frames the industrial sector nationally and in Pennsylvania and outlines existing progress toward industrial decarbonization at both levels. The *Methodology* section further describes current sources of industrial emissions in Pennsylvania (the "emissions baseline" used in this report), the decarbonization levers applied in Strategen's roadmap, and other methodological considerations around subsector decarbonization pathways and costs. The *Roadmap to Industrial Decarbonization* lays out Strategen's developed decarbonization pathways for each of Pennsylvania's industrial subsectors. The *Impacts and Benefits of this Roadmap* section characterizes the resource needs required for these pathways and considers the potential effects of the roadmap on equity and environmental justice and Pennsylvania's economy and jobs. The report concludes with a set of enabling actions for both the public and private sectors that would set Pennsylvania on the decarbonization pathway described here.

Challenges in Industrial Decarbonization

The industrial sector is wide-ranging and includes a diverse set of economic activities, such as manufacture of goods (e.g., pulp and paper products), production of materials (e.g., cement, iron, steel, petrochemicals), and extraction and processing of fossil fuel products (e.g., coal mining, petroleum and gas systems, refining).

When including indirect emissions from industrial electricity use, the industrial sector is the highest-emitting sector in the U.S. economy, responsible for 30% of all greenhouse gas (GHG) emissions in 2021.[2] The majority of industrial emissions (78%) are produced directly at industrial facilities through burning fuel, industrial processes, and other sources, while about 22% of emissions arise indirectly from the use of electricity within the sector.[3] This study focuses on the direct emissions from the industrial sector, and therefore excludes indirect emissions associated with the off-site generation of power that is ultimately used at industrial facilities.[4]

The industrial sector is traditionally considered a "difficult-to-decarbonize" sector of the economy due to the diversity of energy inputs feeding into an array of industrial processes, the need for high temperature heat to drive many of these processes, GHG emissions that are released as byproducts of industrial processes, and increasing demand for many industrial products.

Figure 3, from the U.S. Department of Energy (DOE), illustrates this challenge. High temperature heating, requiring at least 400° Celsius, and process emissions account for roughly half of the emissions from eight of the nation's largest industrial subsectors.[5] The diversity of emissions sources across these subsectors also calls for distinct decarbonization approaches for each. Reducing high heat emissions from steel is a very different challenge than addressing process emissions from cement or low heat emissions from food and beverage processing.

2 EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks," Last modified August 25, 2023. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks. (Hereafter "EPA GHG Inventory").

3 EPA GHG Inventory.

4 Strategen's analysis does not focus on decarbonization of the electric sector and indirect emissions from power generation are not initially assigned to the industrial sector's baseline emissions. However, in the development of decarbonization pathways, electrification is applied as a solution for several industrial subsectors as a cleaner alternative to fossil fuel combustion. For these subsectors, Strategen accounts for the carbon intensity of the power sector in its analysis and gradually reduces emissions over the study period accordingly, based on the assumption that the grid will decarbonize linearly by 2050.

5 Note that these figures include emissions from electricity, which are accounted for separately in Pennsylvania's GHG Emissions Inventory and Strategen's analysis. Source: Scott, K. et al., Pathways to Commercial Liftoff: Industrial Decarbonization, DOE, 2023. https://liftoff.energy.gov/wp-content/uploads/2023/10/LIFTOFF_DOE_Industrial-Decarbonization_v8.pdf. (Hereafter "DOE, Pathways to Commercial Liftoff: Industrial Decarbonization").

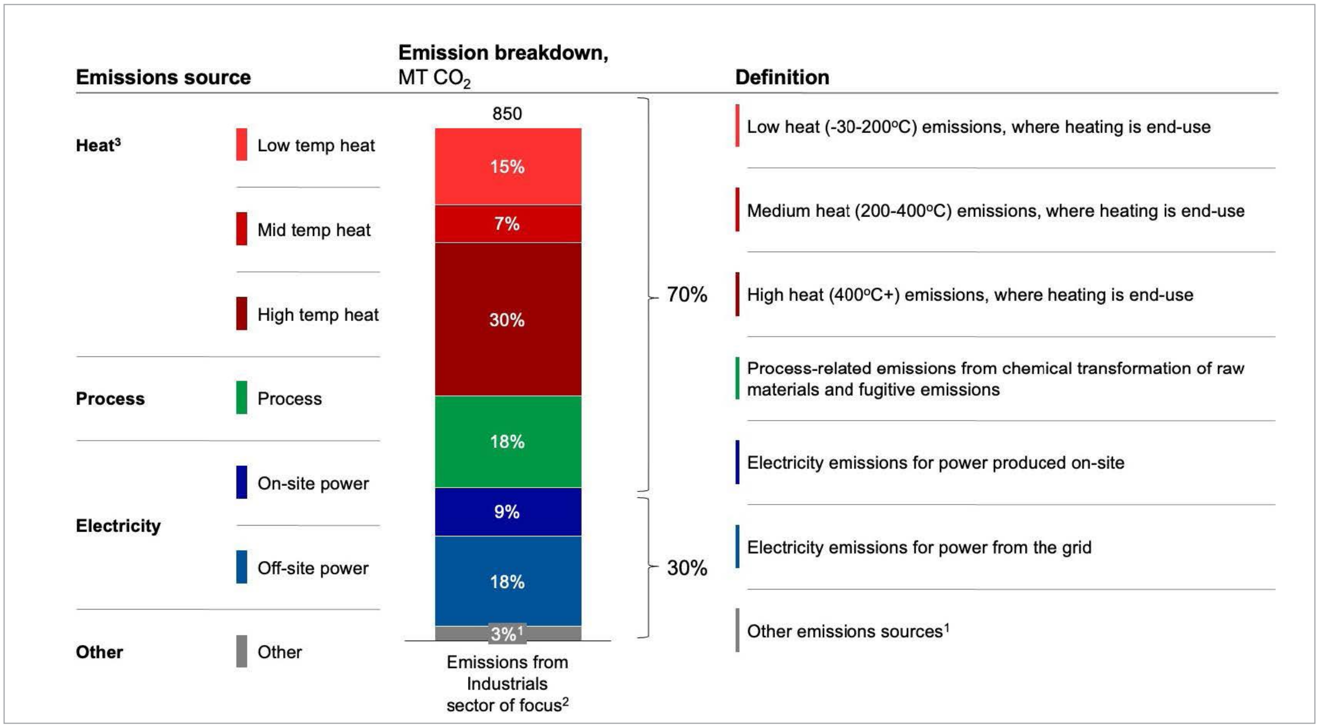


FIGURE 3: Emissions Sources in the U.S. Industrial Sector | *Source: DOE, Pathways to Commercial Liftoff: Industrial Decarbonization*

These challenges mean that the industrial sector is currently behind other sectors in progress toward decarbonization. Most economic sectors are expected to see modest to significant emissions reductions through 2035, with the exception of industry, in which emissions could potentially increase, even with the passage of the Infrastructure Investment and Jobs Act (IIJA) in 2021 and the Inflation Reduction Act (IRA) in 2022, which provided unprecedented levels of funding for decarbonization.[6]

Pennsylvania's Industrial Sector

Pennsylvania is the fourth-largest emitting state in the country for energy-related emissions and the nation's second-largest producer of energy, making it a crucial state in the transition to a zero-carbon economy.[7] The industrial sector is Pennsylvania's largest source of GHG emissions, responsible for 33% of emissions in 2019, the most recent year included in detailed data from the Pennsylvania Department of Environmental Protection's (DEP) GHG Emissions Inventory (*see Figure 4*).[8] Nearly 60% of emissions in Pennsylvania's industrial sector come from fossil fuel combustion, and natural gas accounts for roughly two-thirds of fuel consumption in the sector.[9] The remaining emissions are fugitive emissions from fossil fuel extraction and production (28%) and process emissions (14%).

6 King, B. et al., "Taking Stock 2023: US Emissions Projections After the Inflation Reduction Act," Rhodium Group, July 20, 2023. https://rhg.com/research/taking-stock-2023/.
7 EIA, "Energy-Related CO_2 Emission Data Tables," July 12, 2023. https://www.eia.gov/environment/emissions/state/; EIA, "Primary Energy Production Estimates, Renewable and Total Energy," Accessed October 24, 2023. https://www.eia.gov/state/seds/sep_prod/pdf/P5B.pdf.
8 PA DEP, 2022: Pennsylvania Greenhouse Gas Inventory Report, 2022. https://www.dep.pa.gov/Citizens/climate/Pages/GHG-Inventory.aspx. (Hereafter "Pennsylvania GHG Inventory").
9 Pennsylvania GHG Inventory.

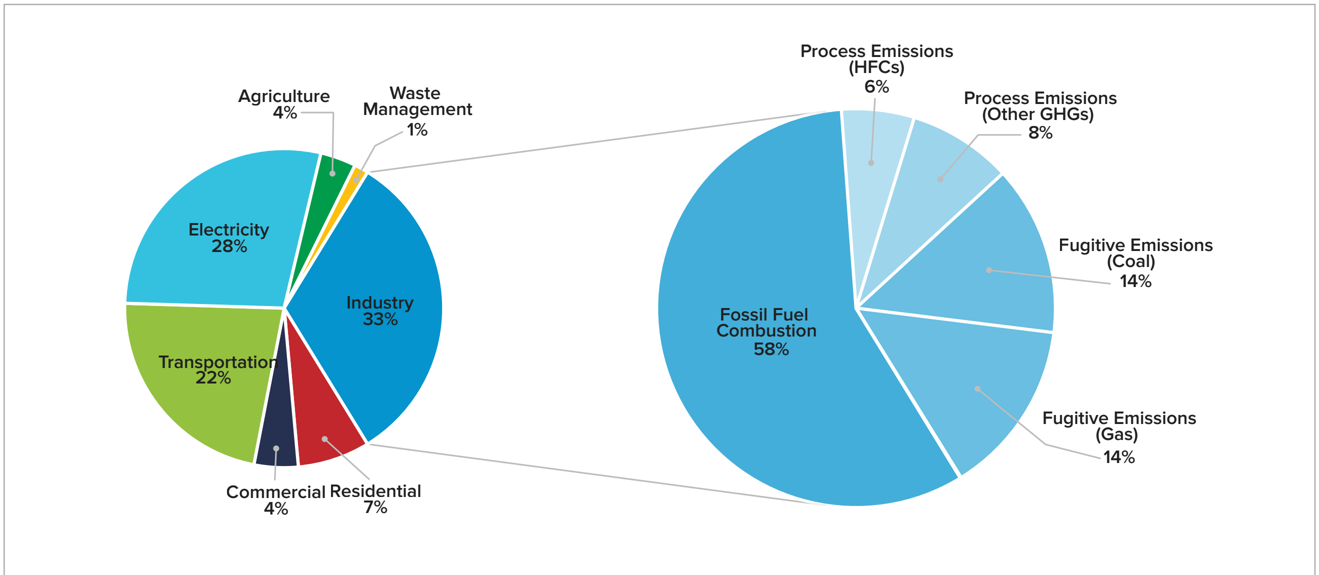


FIGURE 4: Pennsylvania Total and Industrial Sector Greenhouse Gas Emissions (2019) | *Source: PA DEP, Pennsylvania Greenhouse Gas Inventory Report, 2022*

Consistent with national trends, Pennsylvania's industrial sector lags behind other sectors in decarbonization progress. From 2005 to 2019, Pennsylvania reduced its net emissions by 17.6%, driven primarily by reductions in electricity production (which saw a 40.3% decline in emissions), transportation (-13.8%), and residential and commercial buildings (-13%). In contrast, emissions from the industrial sector grew nearly 11% over the same period. Projections in Pennsylvania's Climate Action Plan (CAP), as well as estimates from Strategen's analysis (*see Figure 5*), indicate that, absent further decarbonization actions, industrial sector emissions will remain steady or even increase through 2050.

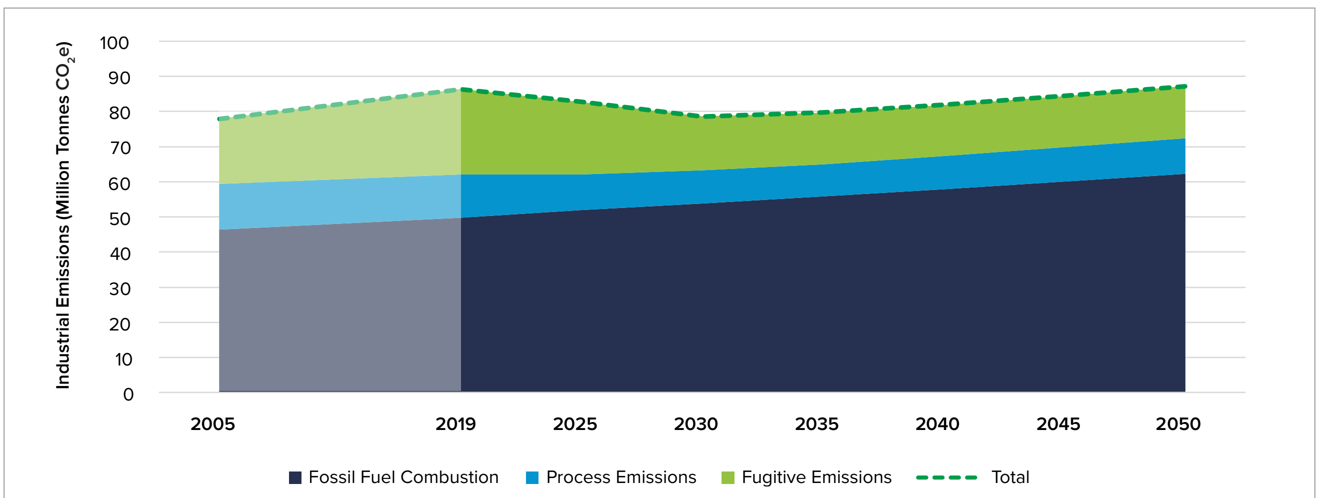


FIGURE 5: Pennsylvania's Industrial Sector Emissions – 2005, 2019, and projected | *Source: Strategen projection, based on the 2022 Pennsylvania GHG Inventory with updated assumptions*

These trends pose a challenge in reaching Pennsylvania's long-term climate goals, established in 2019. Executive Order 2019-01, signed by then-Governor Wolf, set an economy-wide GHG reduction goal of 26% from 2005 levels by 2025 and 80% by 2050.[10] Given current policies and ongoing actions both at the state and

10 Commonwealth of Pennsylvania Governor's Office, "Executive Order 2019-01, Commonwealth Leadership in Addressing Climate Change and Promoting Energy Conservation and Sustainable Governance," January 8, 2019. https://www.oa.pa.gov/Policies/eo/Documents/2019-01.pdf.

federal levels, Pennsylvania is likely to meet its 2025 goal.[11] However, achieving Pennsylvania's mid-century goals will require deeper reductions in GHG emissions throughout the economy, with particular attention needed on difficult-to-abate emissions from the industrial sector.

Existing Progress to Reduce Industrial Emissions

Federal and state policies, coupled with private sector action, have begun to accelerate progress towards decarbonization across the economy, including in the industrial sector. The following two sections summarize developments of note both nationally and in Pennsylvania.

Federal Industrial Decarbonization Efforts

A suite of actions at the federal level, both through legislation and agency initiatives, has created an enabling environment for industrial decarbonization. Such mechanisms can be leveraged to fund or provide support for Strategen's developed pathways. Specific developments of note include:

+ **Grants for industrial decarbonization projects through the IIJA**: The IIJA provided significant funding for industrial decarbonization demonstration and pilot projects. These include $8 billion for Regional Clean Hydrogen Hubs, roughly $800 million for carbon capture demonstration projects at industrial facilities, $750 million in Advanced Energy Manufacturing and Recycling Grants to reduce emissions in industrial facilities, and $400 million in Industrial Research and Assessment Center Implementation Grants specifically for small- and medium-sized manufacturers.[12]
+ **DOE Office of Clean Energy Demonstration's Industrial Demonstration Program**: Jointly funded through the IIJA and the IRA, this program will provide more than $6 billion to projects that reduce emissions in the highest emitting and hardest to abate industries (e.g., iron and steel, cement, chemicals, refining).[13]
+ **Tax credits through the IRA**: The IRA provided a suite of new and updated tax credits that both directly and indirectly support industrial decarbonization. Central among them are the 48C Advanced Energy Property credit, the 45Q carbon capture tax credit, the 45V hydrogen production tax credit, and both production and investment tax credits for clean energy production (45Y and 48E).[14]
+ **Federal government procurement initiatives**: Through Executive Order 14057, President Biden launched a Buy Clean initiative, which directs federal agencies to prioritize the use of domestic low-carbon construction materials (e.g., steel and cement) in federal procurement and federally funded projects, while also increasing the transparency of products' embodied emissions through supplier reporting.[15] The IRA later provided $2.15 billion to the U.S. General Services Administration to acquire and install construction materials and products with lower embodied emissions, with a pilot currently ongoing for concrete, cement, asphalt, steel, and glass.[16]

11 This projection, presented in Pennsylvania's CAP, accounts for increasing power demand and ongoing decarbonization policies like the expiring alternative energy portfolio standard and efficiency improvements from Act 129 in the power sector, while fuel and appliance efficiency mandates are integrated in the transportation and buildings sectors. It assumes Pennsylvania's entrance into the Regional Greenhouse Gas Initiative, which is currently uncertain. It also includes the mandated phase-out of hydrofluorocarbons (HFCs), as required in the federal American Innovation and Manufacturing (AIM) Act of 2020, and the more recent rulemaking *Control of VOC Emissions from Conventional Oil and Natural Gas Sources*, which impacts methane emissions.

12 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.

13 Office of Clean Energy Demonstrations, "Industrial Demonstrations Program," DOE, Accessed October 17, 2023. https://www.energy.gov/oced/industrial-demonstrations-program.

14 Public Law No. 117-169, August 16, 2022. https://www.congress.gov/bill/117th-congress/house-bill/5376/text/rh.

15 The White House, "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability," December 8, 2021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/; Office of the Federal Chief Sustainability Officer, "Federal Buy Clean Initiative," Accessed October 17, 2023. https://www.sustainability.gov/buyclean/. (Hereafter "Federal Buy Clean Initiative").

16 General Services Administration, Interim IRA Low Embodied Carbon Material Requirements, May 16, 2023. https://www.gsa.gov/system/files/Interim%20IRA%20LEC%20Material%20Requirements%20-%20used%20in%20Pilot%20May%202023%2005162023.pdf.

+ **DOE Energy Earthshots Initiatives**: These initiatives are designed to accelerate the development and deployment of the clean energy solutions needed to reach both near- and long-term U.S. decarbonization goals. The Industrial Heat Shot was launched in 2022 to develop cost-competitive industrial heat decarbonization technologies for lowering GHG emissions by at least 85% by 2035. Relatedly, the Clean Fuels & Products Shot and Hydrogen Shot each focus on strategies to bring clean alternative fuels to market, with implications for fossil fuel combustion in industry.
+ **Research on national industrial decarbonization pathway**: In 2023, DOE published two seminal reports outlining actions needed for industrial decarbonization in the United States. The *Industrial Decarbonization Roadmap* focuses on five of the most carbon-intensive manufacturing subsectors (iron and steel, chemicals, food and beverage, petroleum refining, and cement), while the Pathway to Commercial Liftoff: Industrial Decarbonization report additionally addresses pulp and paper, aluminum, and glass.[17]
+ **Phaseout of fluorinated super-emitters**: The American Innovation and Manufacturing Act of 2020 (AIM Act) required the phase-out of super-emitting hydrofluorocarbon (HFCs), which are used as substitutes for now-banned ozone-depleting substances in diverse industrial processes. The Act will result in an 85% reduction in HFC emissions by 2036.[18]

Pennsylvania Industrial Decarbonization Efforts

As previously mentioned, the establishment of a statewide emissions reduction goal and the subsequent release of Pennsylvania's first CAP aligned with that goal are significant steps on the road to economy-wide decarbonization for the commonwealth. The following efforts across the state may also serve to advance emissions reductions in the industrial sector.

+ **Industrial Efficiency and Decarbonization grants**: Federal funding from DOE's Office of Industrial Efficiency and Decarbonization (IEDO) is flowing to multiple Pennsylvania organizations to advance transformational emissions-reducing technologies in the industrial sector. Funded projects include developing bio-based coke technology, piloting hydrogen direct reduced iron processes for iron and steelmaking, and developing high temperature heat pumps for industrial applications.[19]
+ **Onsite Energy Technical Assistance grant**: Supported by additional IEDO funding, Pennsylvania State University (Penn State) was selected as a Regional Onsite Energy Technical Assistance Provider for industry in Pennsylvania, and across the Mid-Atlantic, New York, and New Jersey.[20] In this role, Penn State will help industrial companies evaluate and adopt on-site energy technologies such as combined heat and power, industrial heat pumps, renewable fuels, and others, which can aid in reducing industrial emissions.
+ **Regional Clean Hydrogen Hubs**: In October 2023, DOE announced that two Pennsylvania applications had been accepted as part of the IIJA's Regional Clean Hydrogen Hubs program, making Pennsylvania the only state to participate in more than one hub. One hydrogen hub, spread across West Virginia, Ohio, and Pennsylvania, will produce hydrogen using natural gas and carbon capture, while the other, covering eastern Pennsylvania, Delaware, and New Jersey, will use renewable and nuclear electricity.[21] Both hubs have reported the industrial sector among their target end-users.[22]

17 Cresko, J. et al., *Industrial Decarbonization Roadmap*, DOE, 2022. https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf. (Hereafter "DOE, *Industrial Decarbonization Roadmap*"); DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.
18 Climate and Clean Air Coalition, "Hydrofluorocarbons (HFCs)," Accessed October 17, 2023. https://www.ccacoalition.org/short-lived-climate-pollutants/hydrofluorocarbons-hfcs.
19 Office of Energy Efficiency and Renewable Energy, "Funding Selections: Industrial Efficiency and Decarbonization FOA," DOE, Accessed October 17, 2023. https://www.energy.gov/eere/iedo/funding-selections-industrial-efficiency-and-decarbonization-foa-0.
20 Ibid.
21 Office of Clean Energy Demonstrations, "Regional Clean Hydrogen Hubs Selections for Award Negotiations," DOE, Accessed October 16, 2023. https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations. (Hereafter "DOE, Hydrogen Hubs Selections").
22 MACH2, *Leading the Way in the Clean Energy Transition*, 2023. https://mach-2.com/wp-content/uploads/2023/05/MACH2-Hydrogen-Hub-Application.pdf. (Hereafter "MACH2, Leading the Way"); ARCH2, "A Hub for Hydrogen Energy," Accessed October 18, 2023. https://www.arch2hub.com/. (Hereafter "ARCH2, A Hub for Hydrogen Energy").

- **Tax Credits for Fuels at Industrial Sites**: In November 2022, Pennsylvania passed a tax package that includes credits relevant to industry. One tax credit incentivizes the use of clean hydrogen at facilities that are part of DOE-funded hydrogen hubs by offering $0.81/kg of hydrogen used in manufacturing at eligible facilities.[23] While this may accelerate fuel switching to hydrogen at industrial sites, the package also includes corresponding incentives that could lock in natural gas usage in industry. These include natural gas tax credits for manufacturing at the same facilities receiving hydrogen use credits, as well as at facilities that manufacture petrochemicals and fertilizers. The use of carbon capture technology at petrochemical and fertilizer facilities is listed as one qualification for receipt of the natural gas tax credit, suggesting that perhaps natural gas usage will only be incentivized at facilities reducing emissions through carbon capture. However, this qualification applies only to the extent that carbon capture is cost effective and feasible, as determined "at the discretion of the qualified taxpayer," opening the possibility that manufacturers could potentially claim the natural gas tax credit without any corresponding emissions reduction efforts, through carbon capture or otherwise.
- **Methane Reduction Strategy and Rulemaking**: This rulemaking requires oil and gas companies to diminish leaks from their production and delivery facilities.[24] While the rules specifically target volatile organic compounds, they have the added benefit of reducing fugitive methane emissions. The rules are anticipated to reduce approximately 40% of the methane emissions from Pennsylvania's oil and gas system, from both conventional and unconventional sites, addressing a large portion of the industrial sector's fugitive emissions. Notably, no existing rules target fugitive emissions from underground coal mines, which account for 45% of all fugitive emissions in Pennsylvania, according to the 2022 GHG Inventory.[25]

Proposed Decarbonization Pathways for Pennsylvania

In addition to the efforts outlined above, a number of governmental, private sector, nonprofit, and academic projects have resulted in various proposed pathways for Pennsylvania's decarbonization. While these pathways differ in geographic and sector-specific scope, they all offer elements that address the industrial sector. *Table 1* describes several pathways of note.

23 Public Law 1695, No. 108, November 3, 2022. https://www.legis.state.pa.us/cfdocs/legis/li/uconsCheck.cfm?yr=2022&sessInd=0&act=108.
24 PA DEP, "Reducing Volatile Organic Compounds and Methane in Pennsylvania," Accessed October 24, 2023. https://www.dep.pa.gov/Business/Air/pages/methane-reduction-strategy.aspx. (Hereafter "PA DEP, Reducing VOCs and Methane in Pennsylvania").
25 Pennsylvania GHG Inventory.
26 PA DEP, *Pennsylvania Climate Action Plan*, 2021. https://www.dep.pa.gov/Citizens/climate/Pages/PA-Climate-Action-Plan.aspx.
27 Anasolabehere, S. et al., *A Low Carbon Energy Transition in Southwest Pennsylvania*, Roosevelt Project, 2021. https://www.cmu.edu/energy/roosevelt-project-southwest-pa-case-study-interim-draft-10-12-2021-post.pdf.

Pathway Name	Organization	Description
Pennsylvania Climate Action Plan[26]	PA Department of Environmental Protection (DEP) and Climate Change Advisory Committee	Identifies strategies to reduce GHGs across Pennsylvania's economy, in line with achieving a 26% reduction by 2025 and 80% by 2050 (compared to 2005). The plan's central strategy to address industrial emissions is increasing energy efficiency and fuel switching, although it also proposes enabling actions like increasing combined heat and power, which could also impact industry.
A Low Carbon Energy Transition in Southwest PA[27]	Carnegie Mellon and Massachusetts Institute of Technology	Highlights hydrogen and CCUS as central opportunities for Southwest Pennsylvania. Also provides detailed strategies for plugging and capping legacy oil and gas wells and pursuing advanced manufacturing.
Road Map for Carbon Management and Hydrogen Development [28]	Team Pennsylvania Foundation and Great Plains Institute	Explores the application of CCUS and hydrogen to mitigate emissions and outlines recommendations to accelerate their deployment across the commonwealth. Grew out of Team PA's Energy Horizons Cross-Sector Collaborative, a multi-stakeholder forum comprising public, private, and non-profit organizations that identified CCUS and hydrogen as priority decarbonization levers for Pennsylvania.
Allegheny Conference Energy Task Force Report[29]	Allegheny Conference on Community Development	Focuses on the energy future of the greater Pittsburgh region. Outlines six strategic levers necessary for decarbonization in the region, with emphasis on hydrogen, CCUS, and low-carbon power generation. Grew out of a task force convened by the Allegheny Conference on Community Development comprising private sector and academic institutions.
A Clean Energy Pathway for Southwestern Pennsylvania[30]	Ohio River Valley Institute	Presents a decarbonization pathway for the power sector in southwestern Pennsylvania focused primarily on zero-emissions resources, energy efficiency, increased electrification, and leveraging clean energy imports from outside the region, while minimizing the local need for fossil fuels.

TABLE 1: Selected Decarbonization Pathways Proposed for Pennsylvania

Some of these plans touch on the industrial sector, but Strategen's roadmap is the first statewide analysis prepared with a sole focus on industrial emissions. It aligns with the state's CAP and is informed by both national and international decarbonization research and best practices. This roadmap also differs from prior works by taking a wider aperture on potential decarbonization levers. Several of the above pathways prioritize the role of hydrogen and carbon capture in the commonwealth's decarbonization. Although Strategen's analysis does include both hydrogen and carbon capture, it also features a large role for energy and material efficiency and electrification, as well as production ramp-downs and facility retirements, where appropriate (further detail on these levers is provided in the Methodology section). The result is a comprehensive, independent, and data-driven decarbonization pathway for Pennsylvania's industrial sector that can add to a growing body of public, private, and nonprofit sector decarbonization proposals.

28 Fry, M. et al., *Successful Deployment of Carbon Management and Hydrogen Economies in the Commonwealth of Pennsylvania*, Great Plains Institute, 2022. https://teampa.com/wp-content/uploads/2022/09/Pennsylvania-Carbon-and-Hydrogen-Roadmap-2022.pdf.

29 Allegheny Conference on Community Development, *Our Region's Energy Future: A Strategy for Accelerating Decarbonization, Investment and Inclusive Growth in the Pittsburgh Region*, 2022. https://www.alleghenyconference.org/wp-content/uploads/2022/04/2022_EnergyReport_D.pdf.

30 Goodenbery, J. et al., *A Clean Energy Pathway for Southwestern Pennsylvania*, Ohio River Valley Institute, 2022. https://www.strategen.com/strategen-blog/orvi-clean-energy-southwestern-pennsylvania. (Hereafter "Goodenbery, J. et al., A Clean Energy Pathway").

Methodology

The scope of emissions included in Strategen's analysis of the industrial sector is primarily consistent with definitions employed by the Environmental Protection Agency (EPA) and PA DEP in its *Greenhouse Gas Inventory Report*. That is, it includes emissions resulting from the combustion of fossil fuels in the industrial sector, emissions from diverse industrial processes, and fugitive emissions associated with fossil fuel production.[31] These are all Scope 1 emissions and exclude indirect GHG emissions, such as those produced in the generation of electricity that is used by the industrial sector, or in upstream and downstream processes from suppliers and customers.[32] Strategen's analysis makes use of the latest state GHG inventory, using data for 2019, as the starting point for its proposed industrial decarbonization pathway.

Emissions Baseline

The latest Pennsylvania GHG inventory, published in 2022, identified 86.39 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) emissions from the industrial sector in 2019, an 11% increase from 2005 levels. In 2019, 58% of industrial emissions came from the direct combustion of fossil fuels, 14% were process emissions, and 28% were caused by fugitive emissions, primarily methane, from the fossil fuel extraction and production industries.

Emission Category	Industrial Subsector	2005	2019
Fossil Fuel Combustion / All Sectors	General	46.34	49.75
Process Emissions / Industrial Production	Cement	3.13	1.80
	Lime	0.85	0.71
	Limestone and dolomite	0.55	0.90
	Soda ash	0.11	0.08
	Iron & steel	4.48	3.80
	Urea	0	0.01
Process Emissions / Fluorinated Gases	ODS substitutes	3.56	4.93
	Semiconductors	0.03	0.01
	Power T&D	0.34	0.16
Fugitive Emissions / Coal	Coal mines - Underground	7.67	10.88
	Coal mines - Surface	0.85	0.36
	Coal mines - Abandoned	1.3	0.67
	Gas production	4.81	8.11
Fugitive Emissions / Oil & Gas[33]	Gas T&D	3.89	4.16
	Oil production	0.04	0.06
Total Emissions from Industrial Sector		**77.95**	**86.39**

TABLE 2: Emissions from the Industrial Sector ($MMTCO_2e$) | *Source: PA DEP, Pennsylvania GHG Inventory**
*The PA DEP GHG Inventory was updated on December 15, 2023. However, this is not expected to significantly impact the analysis contained in this report.

31 The fossil fuel combustion emissions category includes the fuel delivered to large customers from other sectors, such as agriculture, construction, and large commercial facilities. As a result, the share of emissions attributed to the commonwealth's industrial sector is likely to be overstated by a small amount, but given the methodology employed to develop the GHG inventory, it is not possible to determine the exact contribution of each of those non-industrial sectors.

32 Scope 1 emissions are direct GHG emissions from an organization's owned or controlled sources, including refrigerants, emissions from combustion in owned or controlled boilers and furnaces, and emissions from fleet vehicles.

33 Fugitive emissions from the oil and gas sector do not include methane emissions from abandoned wells or from super event leaks.

For the GHG inventory, the EPA estimates emissions from fossil fuel combustion using the U.S. Energy Information Administration's (EIA) State Energy Data System (SEDS) and makes projections following indicators from EIA's Annual Energy Outlook (AEO 2022). These emissions are quantified based on the industrial fuel consumption by large customers in the state, and the emission factors associated with each of the fuels consumed.[34] As a result of this methodology, these emissions are not specifically assigned to any individual industrial subsector.

Process emissions are estimated using the EPA's State Inventory Tool (SIT), which follows the same methodology as EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*.[35] These emissions are calculated using data on production from each industry and emission factors for each industrial process, excluding the combustion of fuels. Similarly, fugitive emissions are calculated in the SIT tool using emission factors applied on the number of coal mines, oil and gas wells, and the fuel delivery infrastructure in the state.

For its pathway analysis, Strategen projects 2019 baseline emissions to 2050, based on a similar methodology employed by Pennsylvania for the 2021 CAP, with two minor updates to process and fugitive emissions. First, the CPA projects a reduction in emissions from industrial processes for sectors such as steel and cement production. Although this reduction is not explained in detail in the CPA report, Strategen acknowledges that the use of EPA's projection tools, which are based on past trends, can imply a trajectory of future reductions. In practice, however, assumptions built on these projections may understate the need for explicit actions to move such trends forward. For this reason, Strategen's baseline assumes that industrial process emissions will increase in a base case scenario, following the growth of production across these industrial sectors. Second, the projection of fugitive emissions from the oil and gas sector is further reduced in Strategen's baseline based on the *Pennsylvania Methane Reduction Strategy & Rulemaking*, which passed this year and is expected to eliminate 5 $MMTCO_2e$ of methane emissions by 2030.[36]

Sector-Specific Analyses

Given that the GHG Inventory provides data on emissions from fossil fuel combustion only at an aggregate level across the entire industrial sector, Strategen additionally employed data from the EPA Greenhouse Gas Reporting Program (GHGRP) to quantify emissions by industrial subsector, in order to more accurately identify potential solutions for each category.[37] The GHGRP includes detail on the quantity and sources of GHG emissions from the largest industrial facilities in the commonwealth. These data were used to approximate the share of emissions from fossil fuel combustion to attribute to each industrial subsector. Strategen's approach led to the selection of 20 subsectors across seven categories for analysis of decarbonization strategies in the near- (2030), mid- (2040) and long-term (2050) horizons.

The GHGRP includes reporting from 292 facilities in Pennsylvania, accounting for more than 125 $MMTCO_2e$ in 2019. Approximately 33% of these emissions are from facilities in the industrial sector, while 62% are attributed to power plants, with the remaining 5% from other diverse sources, such as waste management, universities, and biogenic emissions. The industrial share totals 41.4 $MMTCO_2e$ from specific facilities, accounting for 48% of industrial emissions estimated in the state's GHG inventory for 2019.

Under EPA's methodology for the GHGRP, for some subsectors, including cement, lime, and petroleum refineries, all facilities are required to report their emissions, while for other sectors, only the largest facilities (generally those emitting over 25,000 metric tons CO_2e) are required to report. This means that not all facilities are counted in the GHGRP emissions data, and Strategen therefore allocates an additional portion of total CO_2e emissions from the GHG inventory to these sectors to account for smaller facilities. Relatedly, Strategen's analysis also assumes that the decarbonization levers identified in the pathway for each subsector are applicable to both large and smaller facilities, although in execution it may not be practical, cost-effective, or even feasible for all of the smallest-scale facilities to implement these solutions. Through this methodology, Strategen incorporates data from both the Pennsylvania GHG inventory and the GHGRP, adjusted to approximate emissions from smaller facilities where applicable, to estimate the GHG emissions attributable to each individual subsector. The reported and estimated emissions are presented in *Table 3: Pennsylvania industrial GHG emissions in 2019 (thousand metric tons CO_2e).*

34 In its *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, EPA notes that the majority of industrial fuel consumption is attributed to industrial customers, but this category also includes fuel used by the agriculture, mining, and construction sectors, as well as large commercial customers.

35 EPA GHG Inventory.

36 PA DEP, Reducing VOCs and Methane in Pennsylvania.

37 EPA GHG Inventory.

Industrial Subsector		GHG Reporting Program		Estimated	PA GHG Inventory			GHG Share
		Reported Emissions	Reporting Facilities	Total Emissions	Fossil Fuel Combustion[39]	Process	Fugitive	
Fossil Fuel Extraction and Delivery[40]	Oil and gas systems	10,607	large	15,153	2,823	-	12,330	34%
	Coal mines	10,010	large	14,300	2,390	-	11,910	
Fluorinated GHGs[41]	Use of ODS subst.	-	-	4,930	-	4,930	-	7%
	Fluorinated gas production	650	large	928	928	-	-	
	Other HFC, PFC, SF6, and NF3 emissions	114	large	323	153	170	-	
Metals	Iron and steel prod.	6,613	large	9,447	5,647	3,800	-	12%
	Lead and zinc	268	large	382	382	-	-	
	Other metals	653	large	933	933	-	-	
Minerals	Cement production	3,039	all	3,039	1,239	1,800	-	7%
	Lime manufacturing	1,233	all	1,233	523	710	-	
	Glass production	572	large	817	737	80	-	
	Limestone and dolomite	-	-	900	-	900	-	
	Other minerals	207	large	296	296	-	-	
Refineries	Petroleum refineries	3,622	all	3,622	3,622	-	-	4%
Chemicals	Ethanol production	159	large	227	227	-	-	4%
	Hydrogen production	40	large	57	47	10	-	
	Other chemicals	506	large	2,971	2,971	-	-	
Low Heat Subsectors	Pulp and paper	1,882	large	2,688	2,688	-	-	31%
	Food processing and misc. manufacturing	831	large	1,187	1,187	-	-	
	Other industries[42]	388,101	-	22,958	22,958	-	-	
Total[43]		**41,392**		**86,390**	**49,750**	**12,400**	**24,240**	**100%**

TABLE 3: Pennsylvania Industrial GHG Emissions in 2019 (thousand metric tons CO_2e)

38 For sectors in which small facilities are not required to report emissions through the GHGRP, Strategen assumes that the large reporting facilities are responsible for 70% of total emissions in their respective subsectors, with an additional 30% emitted from smaller facilities not included in the reported data.

39 Estimated as the delta between total emissions and process or fugitive emissions. This category is reported in the Pennsylvania GHG Inventory as general emissions from fossil fuel combustion at 49.75 $MMTCO_2$e.

40 GHG emissions from these subsectors are mainly fugitive methane emissions, but also include emissions from stationary combustion.

41 These subsectors are largely affected by the mandated phaseout of HFCs, targeting an 85% reduction in their usage and production by 2036.

42 The Other Industries subsector accounts for the difference between the total fossil fuel combustion emissions reported in the Pennsylvania GHG Inventory and the estimated fuel combustion emissions for all reporting subsectors. While the share of industries in this remaining subsector is unknown based on available data, it contains stationary combustion emissions from a variety of other industrial subsectors, but also from mining, large buildings (e.g., hospitals and universities), construction, and agriculture. Although some of these subsectors are not considered part of the industrial sector, the GHG Inventory's methodology of data collection for fossil fuel usage includes all large customers in the sector's scope. Most of the emissions from this category are attributed to stationary combustion for low heat processes and space heating.

43 Total emissions, as reported in the Pennsylvania GHG Inventory, exclude those from abandoned oil and gas wells, super event leaks, and gas leaks at the facility level.

For the development of the decarbonization roadmap, Strategen assessed these current and projected emissions as a “business-as-usual” baseline, analyzed each industrial subsector to determine its specific energy needs in the future, and identified actions and technologies that could feasibly be implemented as decarbonization solutions through 2050, explained further below.

Decarbonization Levers

To model Pennsylvania’s industrial subsectors and develop a customized decarbonization pathway for the commonwealth, Strategen evaluated the role that several key levers can play in reducing industrial emissions. Strategen modeled the application of these levers beginning in 2025, based on the assumption that it would take at least a year for planning and for corresponding retrofits and facility upgrades.

Additional emergent levers may play a role in industrial decarbonization, particularly for unique processes within certain subsectors, such as new production methods in industries like steel and cement that have high process emissions. These solutions are still nascent, however. Strategen’s roadmap therefore focuses on strategies that are both widely applicable across multiple subsectors and are either commercially available today or are likely to be commercially available in the near future.

Energy Efficiency

Energy efficiency refers to using less energy to produce the same amount of a given product. Examples of energy efficiency include process improvements that lower energy consumption, such as increased heat exchange efficiency, more efficient technologies, combined heat and power, and waste heat recovery. Energy efficiency has been referred to as the “first fuel” for decarbonization as it is one of the easiest and most cost-effective methods to reduce emissions. Energy efficiency solutions have been implemented across multiple sectors for decades, making this one of the most technologically mature and “shovel-ready” decarbonization levers in the industrial sector.[44] Further, most energy efficiency measures result in cost savings to consumers, lowering energy bills and helping cushion the effects of unexpected price spikes.[45] This innate cost effectiveness is a key differentiator between energy efficiency and other decarbonization levers, which might require tax credits, grants, and other government financing support to be economic. While these financial incentives will likely someday cliff, energy efficiency investments are anticipated to continue to be cost saving in the long run. Importantly, energy efficiency is also accessible to manufacturers of all sizes, including small- and medium-scale manufacturers who may not be able to implement capital-intensive fuel switching and carbon capture projects due to economies of scale.

In this analysis, contributions from energy efficiency were applied early in the study period (2025) and maximized until their exhaustion, resulting in an efficiency-first approach to decarbonization. This approach is particularly salient for the industrial sector, in which nearly two-thirds of energy input is lost before reaching its intended purpose.[46] Given that the industrial sector accounts for about a third of Pennsylvania’s total energy consumption and a typical industrial plant spends 30-50% of its operating budget on energy, it is critical to focus on industrial energy efficiency to cost-effectively reduce energy loss, and emissions, as soon as possible.[47]

44 IEA, “Energy Efficiency 2021,” Accessed October 17, 2023. https://www.iea.org/reports/energy-efficiency-2021/executive-summary.
45 Howarth, N. et al., “Energy Efficiency,” IEA, Accessed October 17, 2023. https://www.iea.org/energy-system/energy-efficiency-and-demand/energy-efficiency.
46 Emerson, “Industrial Energy Efficiency Comes of Age Through Digital Transformation,” Reuters, Accessed October 24, 2023. https://www.reuters.com/plus/roadmap-to-industrial-sustainability/industrial-energy-efficiency-comes-of-age-through-digital-transformation. (Hereafter “Reuters, Industrial Energy Efficiency”).
47 Reuters, Industrial Energy Efficiency.

Material Efficiency

Material efficiency includes approaches such as "lightweighting" products, designing them for longer use, material substitution, or increasing material reuse and recycling. As with energy efficiency, material efficiency provides a low-cost opportunity to lower emissions while minimizing the need for other decarbonization technologies.[48] Contributions from material efficiency were applied in the beginning of 2025 and maximized until their exhaustion.

Electrification

Electrification of industrial processes that have traditionally depended on fossil fuels can provide heat for low- and mid-temperature processes (up to 400° Celsius).[49] In many cases, electrification can begin immediately, given existing technology. As a result, electrification begins at the start of the study period in 2025. The CO_2e reductions resulting from electrification are ultimately dependent on the emissions intensity of the power sector, making the decarbonization of electricity generation an imperative to enable deep emissions reductions in electrified industrial applications. For this roadmap, Strategen assumes that power generation in Pennsylvania will be carbon free by 2050, with emissions decreasing linearly over time. This assumed trend towards power sector decarbonization is aided in part by an ongoing transition away from coal in the state, as well as Pennsylvania's potential participation in the Regional Greenhouse Gas Initiative (RGGI), which is intended to reduce CO_2 emissions from generating units.[50]

Fuel Switching

Fuel switching involves replacing the use of incumbent fossil fuels with cleaner fuel sources that release fewer emissions when combusted. Fuel switching is considered a necessary complement to electrification in the industrial sector, given that electric power may be unable to meet the needs of higher temperature industrial processes (above 400° Celsius).[51] Strategen's analysis models clean hydrogen as a central clean fuel, although it is possible that other clean fuels may play a role. For this report, Strategen defines clean hydrogen as hydrogen that meets DOE's clean hydrogen production standard (≤4 kg CO_2e on a lifecycle, or well-to-gate, basis).[52] This roadmap does not include detailed analysis of potential hydrogen sources and their lifecycle emissions, meaning that all uses of hydrogen proposed in Strategen's pathways are assumed to be carbon-free, as hydrogen does not release GHGs when combusted. A qualitative discussion on potential hydrogen sources for Pennsylvania, and their emissions implications, is included in the Impacts and Benefits of this Roadmap section. This analysis assumes widespread commercial availability of clean hydrogen beginning in 2030, given that there is virtually no clean hydrogen production available today and that projects to increase clean hydrogen supply (e.g., Regional Clean Hydrogen Hubs) will take several years to ramp up to full production. This timeline aligns with DOE's clean hydrogen production projections, which estimate 10 MMT available by 2030, with available supply increasing through 2050.[53]

The exception to this 2030 start date for fuel switching is in the pulp and paper subsector, in which biomass was assumed to be available for near-term fuel switching given its existing usage in the subsector. As a result, fuel switching in the pulp and paper subsector begins in 2025. As with hydrogen, Strategen's analysis does not consider the lifecycle carbon intensity of potential biomass sources (e.g., dedicated energy crops, forestry residue, wood, and forest byproducts) for this analysis, meaning biomass combustion is treated as carbon neutral for simplicity. In practicality, any biomass resources used in the industrial sector should be closely studied to ensure that the emissions released during their combustion do not offset those sequestered in feedstock production.

48 Fernandez Pales, A. et al., *Material Efficiency in Clean Energy Transitions*, IEA, Accessed October 17, 2023. https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions.

49 Roelofsen, O. et al. "Plugging In: What Electrification Can Do for Industry," McKinsey & Company, May 28, 2020. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry.

50 EIA, Pennsylvania State Energy Profile; PA DEP, "Regional Greenhouse Gas Initiative," Accessed October 26, 2023. https://www.dep.pa.gov/Citizens/climate/Pages/RGGI.aspx.

51 Pighini, M. et al., Assessment of Green Hydrogen for Industrial Heat, Deloitte, 2023. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/Advisory/us-advisory-assessment-of-green-hydrogen-for-industrial-heat.pdf.

52 DOE, "Clean Hydrogen Production Standard Guidance," Accessed October 24, 2023. https://www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard.

53 Satyapal, S. et al., *U.S. National Clean Hydrogen Strategy and Roadmap*, DOE, 2023. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap. (Hereafter "DOE, National Clean Hydrogen Strategy and Roadmap").

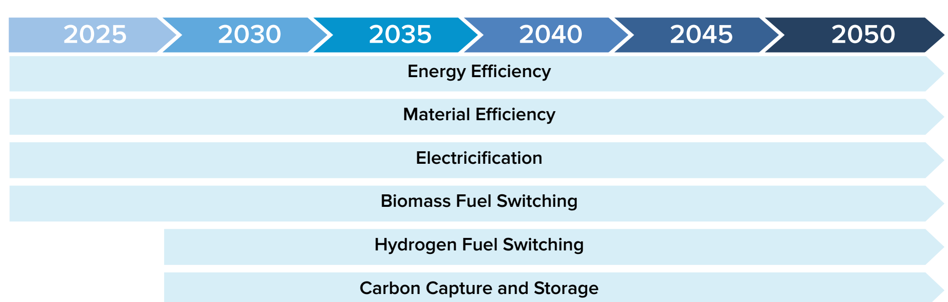
Carbon Capture and Sequestration

Carbon capture and sequestration (CCS) is the capture and storage of combustion and/or process GHG emissions before they are released. Currently, most mature CCS technologies can effectively capture approximately 90% of the CO_2 stream.[54] Strategen's analysis considered various CCS technology types tailored to different industrial subsectors and their associated costs. For this decarbonization pathway, Strategen applied CCS after maximizing all other avenues to reduce emissions, resulting predominantly in the capture of emissions that would otherwise be unabated (namely process emissions).[55] This approach was decided based both on CCS's high costs and limited commercial availability at present. As a result of this limited commercial availability and the need for additional market development before CCS is available for widespread industrial application, Strategen modeled the use of CCS beginning in 2030. This is in line with DOE's *Pathways to Commercial Liftoff: Carbon Management* report, which anticipates near-term CCS applications only in subsectors with high-purity CO_2 streams (given project economics), expanding to most industrial applications post-2030 as the economics become more favorable.[56]

Strategen did not assess or model the potential for utilization of captured carbon, which may be an alternative to sequestration in limited situations. Utilization was excluded for several reasons. Per the International Energy Agency (IEA), the vast majority of captured carbon will need to be permanently sequestered to reach net-zero emissions globally, and the emissions benefits of carbon utilization are highly dependent on the utilization use cases.[57] Using captured carbon for fuel and chemical production (which may be feasible in Pennsylvania) is unlikely to create meaningful climate benefits, given the short-lived nature of these products. Carbon utilization for enhanced oil recovery (EOR) is an option — and one that is well-established today — but the number of potential EOR sites in Pennsylvania is seemingly minimal,[58] and pursuing EOR is likely to run counter to achieving the state's climate goals by promoting continued fossil fuel extraction. As the CCS market matures and novel industrial processes are developed that may make more permanent use of captured carbon (e.g., in concrete production[59]), it is possible that utilization may play a small role in Pennsylvania's industrial decarbonization and potentially serve to offset some costs associated with carbon capture.

Ramp-downs and Retirement

This category refers to production ramp-downs and facility retirements Strategen considered for certain industrial subsectors. In some industrial use cases (e.g., natural gas extraction), Strategen modeled production declines due to decreasing demand for fossil fuel products as a result of other decarbonization efforts. Retirements were only considered for certain facilities in Pennsylvania that were identified to be too expensive to decarbonize and would reach the end of their useful lives during the study period.



Note: This figure excludes production ramp-downs and facility retirements, which were considered on a case-by-case basis.

FIGURE 6: Deployment Timing for Decarbonization Levers in Strategen's Roadmap

54 Moseman, A. and Herzog, H., "How Efficient Is Carbon Capture and Storage?" MIT Climate Portal, February 23, 2021. https://climate.mit.edu/ask-mit/how-efficient-carbon-capture-and-storage.

55 The exception is the application of carbon capture technology to some iron and steel combustion emissions.

56 Fahs, R. et al., *Pathways to Commercial Liftoff: Carbon Management*, DOE, 2023. https://liftoff.energy.gov/wp-content/uploads/2023/04/20230424-Liftoff-Carbon-Management-vPUB_update.pdf. (Hereafter "DOE, Pathways to Commercial Liftoff: Carbon Management").

57 Fajardy, M., "CO_2 Capture and Utilization," IEA, Accessed October 17, 2023. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/CO2-capture-and-utilisation.

58 Great Plains Institute, *Pennsylvania: Implementing Carbon Capture and Storage Technology*, 2021. https://carboncaptureready.betterenergy.org/wp-content/uploads/2021/06/PA_5_25_2021.pdf.

59 Talati, S., Merchant, N. and Neidl, C., *Paving the Way for Low-Carbon Concrete*, Carbon180, 2020. https://static1.squarespace.com/static/5b9362d89d5abb8c51d474f8/t/5fd95907de113c3cc0f144af/1608079634052/Paving+the+Way+for+Low-Carbon+Concrete.

Portfolio Cost

The cost of this decarbonization portfolio was determined on a $/metric ton abated basis for each decarbonization solution within each subsector to arrive at an all-in cost. This analysis relied on third-party data from a diverse set of publicly available sources to approximate the cost of implementing each emissions reduction lever across each subsector. Costs were assessed and incorporated using two complementary methodologies. The first focused on implementation costs through information on capital expenditures for existing projects but excluded operating expenditures such as fuel and electricity costs.[60] The second method relied on levelized costs of abated emissions, meaning that the cost data integrated factors including the asset's capital and operating costs, and the projected emission reductions through its operational period. The levelized cost approach was used for levers like carbon capture and storage, which are an addition to the industrial asset rather than a replacement of the production technology or underlying fuel inputs. Levelized cost data were relied on for other subsector-specific levers, following data availability.

Arriving at the overall portfolio cost necessitated estimating future costs for the decarbonization levers outlined above. This estimation was particularly important for solutions such as clean hydrogen and CCS, which are minimally used today and expected to decline in cost over the coming decades. Strategen estimated future costs by applying rates of cost decline consistent with assumptions for developing technologies from the National Renewable Energy Laboratory (NREL). These rates follow the cost trends of CCS retrofits in NREL's Annual Technology Baseline across its conservative, moderate, and advanced scenarios.[61]

As previously mentioned, recent federal and state laws include tax incentives for a range of technologies and retrofits that can support industrial decarbonization. Strategen's pathway analysis only considered the 45Q tax credit (for CCS), which reduces the cost of capturing carbon by $85/metric ton, assuming prevailing wage and apprenticeship requirements are met, and the carbon is sequestered (not utilized). The 45Q benefit, provided through the IRA, applies to projects capturing at least 12,500 metric tons of CO_2 per year that are constructed before January 1, 2033, although the credits can be claimed for 12 years after the carbon capture equipment is placed in service. Strategen assumes that 45Q will not be extended after its initial expiration, and therefore does not model the continued availability of the tax credit beyond 2045, at the latest. It should be noted, however, that only 15% of the CCS included in Strategen's roadmap would be implemented prior to 2033 and therefore eligible for the 12 years of 45Q credits.

Strategen opted to exclude tax credits related to operating costs and those that would require more detailed assumptions on specific projects in order to accurately model. For example, tax credits for clean energy generation and hydrogen production and usage have been excluded as they apply only to operating costs. Strategen also excluded the federal 48C Advanced Energy Property Credit, which, while a potentially powerful resource to support emissions-reducing facility retrofits at industrial sites, only applies to decarbonization projects that would reduce a facility's overall GHG emissions by at least 20%.[62] Unlike other tax credits which have no federal funding limit, there is a $10 billion cap on 48C credits, and $4 billion of that must go to projects located in census tracts designated as "energy communities." Given the detail required to estimate emissions reductions and other specific project characteristics at the facility-level, as well as uncertainty in how DOE will allocate limited funding resources in both energy communities and non-energy communities, Strategen conservatively did not integrate this tax credit into its pathway analysis.

60 A simplifying assumption for new industrial processes, such as DRI for steel making, is that operating costs will be largely offset by current operating costs.

61 National Renewable Energy Laboratory, "2023 Electricity ATB Technologies and Data Overview," Accessed October 24, 2023. https://atb.nrel.gov/electricity/2023/index.

62 DOE is accepting applications that would result in a 20% reduction in scope 1, scope 2, or sub-unit emissions, but applications will be evaluated on their combined scope 1 and scope 2 emissions impacts facility wide. See https://www.irs.gov/pub/irs-drop/n-23-44.pdf for more detail on credit requirements.

Roadmap to Industrial Decarbonization

This roadmap outlines Strategen's proposed pathways to decarbonize each of the following major industrial subsectors in Pennsylvania:

+ Fossil fuel extraction and delivery, including both oil and gas systems and coal mines.
+ Iron and steel production.
+ Other metal processing and fabrication, including the production of lead, zinc, and other metal products.
+ Minerals, including cement and lime production and the use of other naturally occurring mineral deposits.
+ Chemicals manufacturing, including petrochemicals, ethanol, hydrogen, and other chemical products.
+ Petroleum refining.
+ Glass production.
+ Pulp and paper product manufacturing.
+ Food processing and miscellaneous manufacturing, which are grouped together due to their similar emissions profiles and production processes.
+ Other low-heat sources of emissions, which includes emissions from stationary fossil fuel combustion and space heating reported in PA's GHG Inventory, but not attributed to the subsectors listed above.
+ Fluorinated greenhouse gases, including both the production of these gases and their use in various industrial processes.

The portion of Pennsylvania's industrial emissions attributable to each of these subsectors is displayed in *Figure 7.*

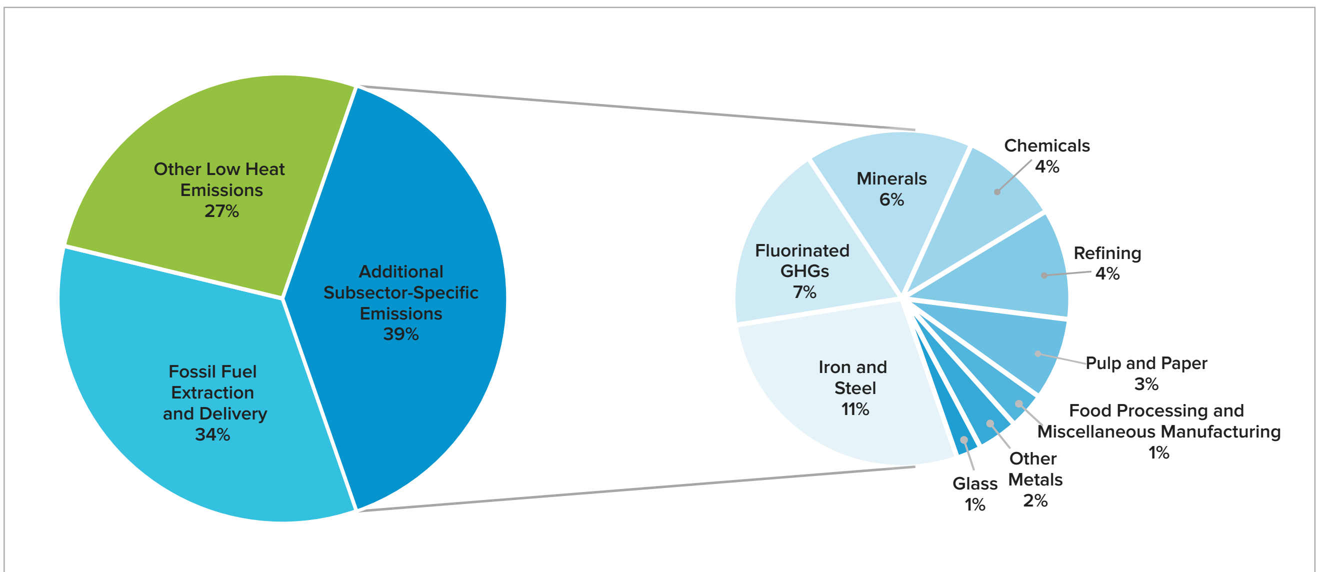


FIGURE 7: Breakdown of Pennsylvania's Industrial Emissions, by subsector (2019)

The analysis of each of these categories includes an assessment of the subsector's presence in Pennsylvania, its overall emissions, and the sources of these emissions. Strategen's roadmap then outlines a decarbonization pathway for each subsector, using the levers described above, and comparing against the subsector's business-as-usual emissions. Each pathway presents emissions reductions by 2030 and 2050 and reports the unsubsidized cost of achieving those reductions. Lastly, each section concludes with a set of key takeaways that summarize the major points of each subsector analysis. The last section of the roadmap synthesizes all subsector pathways for a comprehensive view of Pennsylvania's industrial decarbonization through 2050.

Subsector-Specific Pathways

Fossil Fuel Extraction and Delivery

Pennsylvania is a major fossil fuel producer in the country. It is the second largest natural gas producer after Texas, and the third largest coal producer after Wyoming and West Virginia. The production and delivery systems of these fuels are major sources of GHG emissions, mostly from fugitive methane. Since methane is more efficient than CO_2 at trapping heat in the atmosphere, methane leaks have a larger warming effect than the CO_2 resulting from the burning of the same gas, even considering that burning a metric ton of methane results in 2.75 metric tons of CO_2. The GWP of methane is conservatively estimated at 25 (in a 100-year period) in the federal and state GHG inventories, meaning that a metric ton of methane is equivalent to 25 metric tons of CO_2e.[63] The 2022 Pennsylvania GHG inventory estimates fugitive emissions of methane from the coal, oil, and gas sectors to be responsible for 24.24 $MMTCO_2e$, or 28% of the industrial GHG emissions in the state. The following figure summarizes the sources of industrial fugitive emissions reported in the PA inventory.

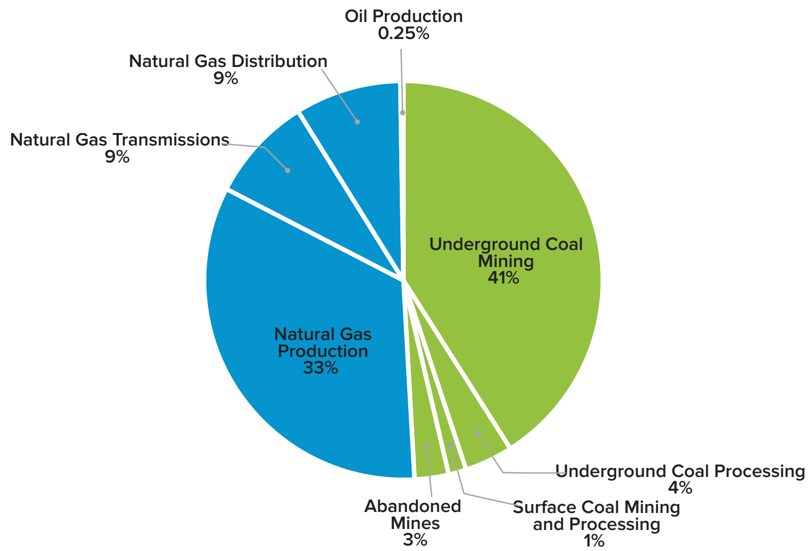


FIGURE 8: Fugitive GHG Emissions from the Fossil Fuel Industry, 2019

In addition to the fugitive emissions reported in the GHG Inventory, the sector also produces emissions from combusting fuels for heat and power. Using data from EPA's GHG Reporting Program (GHGRP), Strategen estimated this activity to account for 5.2 $MMTCO_2e$ in 2019. Together, emissions from fossil fuel combustion and fugitive emissions make up 34% of total industrial emissions in PA.

Importantly, these values only represent CO_2 emissions and fugitive methane emissions from normal system operations.[64] The EPA inventory and reports do not capture emissions from major incidental leak events that release large quantities of gas in a short period of time and that are rarely reported.[65] Two examples of the potential scale of these super-emitter events are the leak in Cambria County in Pennsylvania, which released over 1.4 billion cubic feet of methane (over 27,000 metric tons of CO_2e) through 14 days in November 2022,

63 Methane has a short lifetime in the atmosphere of about 12 years, after which it is decomposed into water and CO_2. Its 25 GWP value is an averaging over 100 years to make it more comparable to CO_2 in terms of CO_2e, however another common GWP is 87 when averaged over 20 years. This high warming potential and its short lifetime, as compared to CO_2, make it a priority for the efforts to mitigate global warming and, according to the IPCC, one of few options to keep warming levels below 1.5°C in the near term.

64 The EPA tools used in the GHG inventory assessment utilize emission factors for different pieces of infrastructure and parts of the production and delivery processes to estimate fugitive methane emissions and CO_2 emissions from flaring.

65 Satellite imagery technology is being used to detect super-emitter events. Examples of this include efforts sponsored by the UN (MARS), the NASA (EMIT), and the European Space Agency (Satellite Sentinel-5P).

and the XTO Energy natural gas well in Ohio that emitted 60,000 metric tons of methane (1.5 $MMTCO_2e$) over the course of 20 days in 2018.[66] Consistent with Pennsylvania's GHG Inventory, this report only quantifies emissions from normal system operations, but it lists recommendations to address all emissions.

Oil and Natural Gas Systems

Oil and gas systems broadly refer to oil and gas production, transmission, and distribution processes. In 2022, Pennsylvania's natural gas production accounted for 19% of the U.S. marketed gas production,[67] making it the second-largest natural gas producer in the nation[68]

In 2019, there were an estimated 70,000 oil and gas wells in the commonwealth, including both conventional and unconventional natural gas wells with an annual production of approximately 6.9 million cubic feet.[69] Conventional resources are those that can be accessed using vertical wells, with minimal stimulation, while unconventional resources have geologic characteristics that require horizontal wellbores and hydraulic fracturing to attain economic production volumes.[70] An estimated 99% of Pennsylvania's natural gas production comes from unconventional wells, though the number of conventional wells is significantly higher.[71] Oil production is a significantly smaller industry in Pennsylvania, and the commonwealth was responsible for less than 1% of national crude oil production in 2019.[72]

Commensurate to its production, Pennsylvania also has approximately 9,200 miles of interstate gas transmission pipelines and 1,200 miles of intrastate gas transmission pipelines. In addition, there are nearly 80,000 miles of gas distribution pipelines in the state.[73]

The first step in the oil and natural gas production process is drilling. Drilling a well can take one to two weeks, depending on whether the well is conventional or unconventional.[74] Once drilling is complete, natural gas is transported to processing plants, where it is treated to remove impurities.[75] Processing can involve different stages and pieces of equipment, including separators, which separate different fluid streams, and dehydrators, which remove water.[76] Once the gas has been processed to meet pipeline quality requirements, it can be moved over long distances via transmission pipelines. Flow through the pipeline is maintained by compressor stations placed along the pipeline.[77] After gas reaches distribution centers, it travels through a small-diameter distribution pipeline network made up of mains and smaller service lines that provide gas directly to end-users.[78]

Strategen's analysis focuses on two primary types of emissions for this sector: methane leaks and CO_2 resulting from methane combustion. Virtually all the subsector emissions come from the natural gas systems, with oil production representing less than 1% of emissions. Fugitive and vented methane emissions across the natural gas

66 PA DEP, *Equitrans Rager Mountain Order*, December 8, 2022. https://files.dep.state.pa.us/RegionalResources/SWRO/SWROPortalFiles/Equitrans_Rager_Mountain_Order_12-8-2022.pdf; Mufson, S., "A Blowout Turned an Ohio Natural Gas Well into a Methane 'Super-Emitter,'" Washington Post, December 16, 2019. https://www.washingtonpost.com/climate-environment/a-blowout-turned-an-ohio-gas-well-into-a-methane-super-emitter/2019/12/16/fcbdf622-1f9e-11ea-bed5-880264cc91a9_story.html.

67 Marketed gas excludes the natural gas used in the system for repressuring, quantities vented and flared, and fugitive emissions.

68 EIA, "Pennsylvania State Energy Profile," Last modified November 17, 2022. https://www.eia.gov/state/print.php?sid=PA. (Hereafter "EIA, Pennsylvania State Energy Profile").

69 EPA, "State Inventory and Projection Tool (SIT): Natural Gas and Oil Module," 2023, https://www.epa.gov/system/files/other-files/2023-06/Natural%20Gas%20and%20Oil%20Module.xlsm. (Hereafter "EPA, Natural Gas and Oil Module"); EIA, "Natural Gas: Pennsylvania Natural Gas Marketed Production," Last modified September 29, 2023. https://www.eia.gov/dnav/ng/hist/n9050pa2a.htm.

70 British Columbia Ministry of Natural Gas Development and Minister Responsible for Housing, *Conventional Versus Unconventional Oil and Gas*, Accessed October 24, 2023. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/natural-gas-oil/petroleum-geoscience/conventional_versus_unconventional_oil_and_gas.pdf.

71 Kelso, M., "2021 Production from Pennsylvania's Oil and Gas Wells," FracTracker Alliance, April 28, 2022. https://www.fractracker.org/2022/04/2021-production-from-pennsylvanias-oil-and-gas-wells/.

72 EIA, "Petroleum & Other Liquids: Crude Oil Production," Last modified September 29, 2023. https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm.

73 Pipeline and Hazardous Materials Safety Administration, "2010+ Pipeline Miles and Facilities," U.S. Department of Transportation, Last modified April 10, 2023. https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-mileage-and-facilities.

74 Pennsylvania Independent Oil and Gas Association (PIOGA), "Exploration/Development," Accessed October 24, 2023. https://pioga.org/education/exploration-development/; PIOGA, "PA Oil and Gas," Accessed October 24, 2023. https://pioga.org/education/pa-oil-and-gas/.

75 Canada's Oil and Gas Natural Producers, "Natural Gas Extraction," Accessed October 24, 2023. https://www.capp.ca/natural-gas/drilling-and-fracturing/.

76 EIA, "Natural Gas Explained: Delivery and Storage," Last modified February 17, 2023. https://www.eia.gov/energyexplained/natural-gas/delivery-and-storage.php.

77 EIA, "Natural Gas Explained: Natural Gas Pipelines," Last modified November 18, 2022. https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php. (Hereafter "EIA, Natural Gas Pipelines").

78 EIA, Natural Gas Pipelines.

production, transmission, and distribution segments are estimated to be 12.3 $MMTCO_2e$ and account for nearly 84% of the subsector emissions.[79] Fuel combustion is estimated to account for the remaining 2.8 $MMTCO_2e$ of the subsector emissions.[80] The total estimated emissions from oil and gas systems in 2019 are 15.2 $MMTCO_2e$, or 17.5% of total industrial emissions.

The fugitive emissions from the natural gas system were segmented for this analysis into fugitive emissions from production, transmission, and distribution. The primary source of fugitive emissions is the production segment, responsible for 66% of leaks and vented gas in the sector. Within this segment, pneumatic controllers are estimated to account for 40% of emissions. The transmission segment is responsible for 17% of the subsector's fugitive and vented emissions, primarily from compressor station operations. The combustion emissions from the transmission subsector are also tied to compressor station operations since fossil fuel combustion is typically used to power compressors. The remaining fugitive emissions come from the distribution segment and are primarily attributed to leaks from distribution mains and service lines.

Decarbonization Pathway

Fugitive and vented gases from the fossil fuel production and delivery system in the U.S. comprise about a third of the country's total methane emissions. As methane has a high GWP, methane reduction has become a primary area of focus in strategies to reduce GHG emissions. As the use of coal decreases in the country, federal plans, rulemakings, and incentives are focusing on the oil and gas sector and the available technologies to reduce fugitive emissions, targeting 30% to 40% reductions by the end of the decade.[81] In the longer term, the IEA estimates that 75% of methane emissions from the oil and gas sector can be abated using existing technologies.[82] This pathway is focused on the natural gas subsector and considers its projected growth to 2050 as well as recent state regulation targeting fugitive emissions. According to the EIA's AEO for 2023, natural gas production is projected to grow at a 0.5% annual rate in the United States, leading to a 15% overall growth from today to 2050. Of note, EIA projects that the majority of growth in domestic natural gas production will not come from Appalachia, but rather, output is expected to decline in this region in the near term and steadily climb back to current levels of production by 2050.[83]

In Pennsylvania, recent amendments to the environmental protection rules and regulations (Title 25),[84] in line with federal rules, require oil and gas companies to adopt "reasonably available control technology (RACT)" to limit emissions from conventional and unconventional sources of volatile organic compound (VOC) emissions.[85] Overall, the rule aims for the mitigation of 40% of the subsector's fugitive emissions in the short term (representing one-third of total subsector emissions). The pathway assumes that this reduction can be completed by 2030 and carried forward.

Because industrial use in Pennsylvania is a significant source of natural gas demand, decreases in fuel use from other industrial sectors resulting from Strategen's proposed decarbonization levers are incorporated as part of the decarbonization pathway for the natural gas production subsector, leading to an additional 6% reduction in the natural gas demand by 2050. Strategen assumed that this reduction in demand would result in a proportional decrease in overall subsector emissions.

Another key lever in the natural gas systems pathway is leak detection and repair (LDAR). LDAR generally refers to locating and repairing leaks throughout the natural gas supply chain, including production, gathering, processing,

79 Pennsylvania GHG Inventory.
80 While combustion emissions exist across the system, the vast majority come from compressor stations in the transmission segment.
81 These programs include the Methane Emissions Reduction Program created by the IRA (with $1.55 billion in funding), the U.S. Methane Emissions Reduction Action Plan that includes proposed EPA rule updates and emission limitations on new and existing oil and gas sources (under the Clean Energy Act, known as Quad-O).
82 De Oliveira Bredariol, T., "Methane Abatement," IEA, Accessed October 19, 2023. https://www.iea.org/energy-system/fossil-fuels/methane-abatement.
83 Ohio River Valley Institute, *Frackalachia Update: Peak Natural Gas & What It Means for the Future*, August 22, 2023. https://ohiorivervalleyinstitute.org/wp-content/uploads/2023/08/Frackalachia-Update-Presentation.pdf.
84 See *Control of VOC Emissions from Conventional Oil and Natural Gas Sources* and *Control of VOC Emissions from Unconventional Oil and Natural Gas Sources*, available at: https://www.dep.pa.gov/Business/Air/pages/methane-reduction-strategy.aspx.
85 These sources include natural gas-driven continuous bleed pneumatic controllers, natural gas-driven diaphragm pumps, reciprocating compressors, centrifugal compressors, fugitive emissions components and storage vessels installed at unconventional well sites, gathering and boosting stations and natural gas processing plants, as well as storage vessels in the natural gas transmission and storage segment.

transmission, and distribution. There are several techniques that can be categorized as LDAR, such as the use of infrared cameras to detect methane leaks. The new Pennsylvania rulemaking requires quarterly or annual LDAR inspections for natural gas wells that meet certain production levels, as well as gathering and boosting facilities and natural gas processing facilities.[86] Strategen assumes that additional reductions in fugitive emissions will be made using LDAR as the technologies continue to improve and be applied in other segments like transmission and distribution. New detection methods are currently under development, including continuous monitoring systems and aerial and satellite surveillance instruments, that could more reliably identify large fugitive emissions sources.[87]

The pathway for the gas subsector, after accounting for adjusted demand and the new rule, focuses on potential solutions for each of the three segments of the natural gas sector. Within the production segment, pneumatic controllers are the largest source of fugitive emissions, accounting for almost half of the segment's contribution. Pennsylvania's VOC Rule is expected to lead to a large reduction in methane emissions from these devices,[88] and while it will not fully eliminate them, these could be reduced by 95% from current levels.[89] While there are technologies that could be used to eliminate the remaining 5% of emissions from pneumatic controllers, Strategen chose to exclude these from the pathway, as the upgrades would incur significant costs with limited impact on the total emissions.

Without more detailed information on the division of the remaining emissions sources within the production segment, Strategen assumed that a combination of LDAR and general technology upgrades would be used to mitigate production emissions. The reductions from LDAR begin in 2025, since LDAR is a currently available technology, and are incremental to any reductions from LDAR from the VOC rule. Technology upgrades are the same type of improvements promoted by the VOC rule mandates. Strategen is assuming that the VOC rule is fully implemented by 2030, and that the VOC rule covers all economic technology upgrades prior to 2030. Since some LDAR requirements are included in the VOC rule, two-thirds of the remaining production segment reductions are attributed to technology upgrades and one-third is attributed to LDAR. Since many emissions reduction opportunities have been identified as ready-to-implement, there is a sharp decrease in emissions in the near-term, reaching a reduction of 56% from the initial 2019 production emissions level by 2035. An additional 6% reduction in the production sector, relative to 2019 levels, is achieved by 2050, using emerging tools and technologies to abate more difficult-to-decarbonize sources.

The best option for mitigating combustion emissions from engines in the transmission segment is replacing internal combustion engines with electric motors, powered by either distributed renewable and storage systems or using energy from the electric grid. One key challenge for the electrification of compressor stations is finding a source of electricity. Some sites may be suitable for grid connection, but other more remote sites may require the installation of distributed generation. Depending on the size of the engine required, the installation of distributed generation could require high levels of capital costs. These technologies are generally ready for deployment, but since this solution involves relatively large capital expenses, Strategen assumes that deployment will occur gradually, replacing aging equipment as it becomes economic. The gradual adoption of electric motors will eliminate combustion emissions from gas engines as the grid fully transitions to clean energy by 2050. In the developed pathway, Strategen assumes that internal combustion engines are gradually converted to electric motors, beginning in 2025. By 2050, 80% of combustion emissions are mitigated through electrification and efficiency gains. During this transition, the electric grid is assumed to fully decarbonize, reducing emissions from this sector over the analysis period.

86 PA DEP, Reducing VOCs and Methane in Pennsylvania.

87 IEA, "Methane Tracker 2020: Methane Abatement Options," Accessed October 19, 2023. https://www.iea.org/reports/methane-tracker-2020/methane-abatement-options.

88 The VOC rule requires continuous bleed pneumatic controllers to operate at a bleed rate lower than 6.0 standard cubic feet per hour, classifying them as low-bleed pneumatic controllers. Based on the data for the Appalachian Eastern Overthrust Basin, as estimated in EPA's Annex 3.6 for the 2023 Greenhouse Gas Inventory, the emissions factor for low-bleed pneumatic controllers is only 5% of that for high-bleed controllers.

89 The replacement of pneumatic controllers with either instrument air or mechanical controllers would be required for full decarbonization of the segment. Since the new rule will lead to significant reductions in emissions from pneumatic controllers through replacement with lower-emissions devices in the near-term, Strategen decided not to include the adoption of instrument air or mechanical controllers as part of the decarbonization pathway for this sector. The remaining emissions from controllers will be relatively small, and the economics of replacing the low-bleed controllers so early in their lifetime are less favorable based on the level of reductions achieved.

A large portion of fugitive emissions in the transmission segment are attributed to centrifugal and rotating compressors. These emissions are reduced by 95% by 2050 at a linear rate, based on commitments made by industry members.[90] The methods for compressor emissions reductions include a variety of different solutions and are broadly classified as technology upgrades. The remaining sources in the transmission segment are grouped as venting, which is decarbonized by 95% by 2050 at a linear rate using vapor recovery units (VRUs), and general fugitives, which are reduced by 60% by 2050. VRUs are systems that capture vapors from low-pressure vent sources, including storage tanks and compressors.[91] The solution used for decarbonizing general fugitives is LDAR.

Emissions from the distribution segment are reduced through distribution pipeline retrofits with either plastic or protected steel, categorized more broadly as technology upgrades. Strategen estimates that 95% of emissions from distribution pipelines will be abated through pipeline replacement programs by 2050. This figure is based on the ratio of emissions factors between cast-iron and protected steel distribution pipelines.[92] The remaining 5% of emissions are attributed to difficult-to-detect leaks and pipeline mishaps, such as unintentional dig-ins, and are not abated in the pathway.

Overall, the oil and gas subsector has the potential to reduce GHG emissions by 75% from 2019 levels.

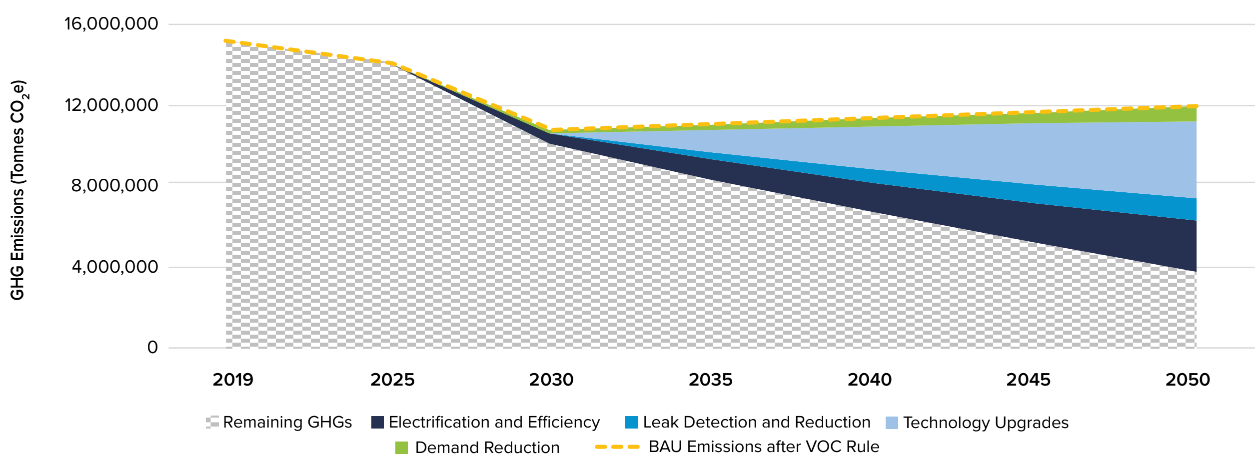


FIGURE 9: Oil and Gas Decarbonization Pathway (2019-2050)

Portfolio Cost

The oil and gas decarbonization pathway will cost $2.9 billion in aggregate, requiring $2 billion for electrification measures and the remainder for technology upgrades. The assumed 40% reduction resulting from the VOC rule covers economic technology and efficiency improvements that are currently available, and thus no net cost was assigned to these upgrades. Other technology upgrades include improvements with venting in the transmission segment, the use of new pipelines in the distribution segment, and compressor improvements. The cost of these upgrades is taken from the UN Environment Programme's *Global Methane Assessment*.[93] Electrification costs are based on estimates for industrial electrification from DOE's *Pathways to Commercial Liftoff: Industrial Decarbonization* report. Leak detection and reduction measures are assumed to become available at a net positive cost as fines for methane emissions are implemented.[94]

90 The Environmental Partnership, "Compressor Program for Onshore Oil and Natural Gas Transmission Operations," Accessed October 24, 2023. https://theenvironmentalpartnership.org/what-were-doing/compressor-program/.
91 EPA, "Vapor Recovery Units," Last modified August 2, 2023. https://www.epa.gov/natural-gas-star-program/vapor-recovery-units.
92 EPA, Natural Gas and Oil Module.
93 United Nations Environment Programme, *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions*, 2021. https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions. (Hereafter "UNEP, Global Methane Assessment").
94 The 2022 Inflation Reduction Act created the methane fee, which will effectively start implementation in 2026 and will serve as a financial incentive for fossil fuel companies to comply with EPA regulations. The program is assisted by an EPA grant program to help pay for emission reduction equipment and procedures.

Key Takeaways

+ The oil and gas subsector is responsible for 17.5% of annual industrial emissions in Pennsylvania. These emissions come from oil and natural gas production, transmission, and distribution, and include vented and fugitive emissions, as well as combustion emissions.
+ The recent final-omitted rulemakings regarding VOC emissions in Pennsylvania will have the benefit of significantly reducing methane emissions from pneumatic controllers, one of the major emissions sources in the natural gas production process.
+ The following solutions can be utilized to reduce oil and natural gas system emissions from 2019 levels by 75% by 2050:
  - Electrification of compressor stations in the natural gas transmission system, using a combination of grid electricity and distributed energy resources.
  - Implementation of LDAR systems to identify and repair large methane leaks in equipment across production, transmission, and distribution processes.
  - Replacement of cast-iron and unprotected steel distribution pipelines with protected steel or plastic pipelines
  - Reduction in natural gas demand, due to the decarbonization of other industrial sectors in Pennsylvania.
+ The implementation of this portfolio of solutions will cost $2.9 billion in aggregate.

Coal Mines

In 2021, Pennsylvania's coal industry accounted for 7.4% of total U.S. coal production, including 16% of the country's bituminous coal (40.42 million short tons) and all of U.S. anthracite coal (2.04 million short tons). Bituminous and anthracite are the leading types of coal used for power generation and industrial processes, respectively.[95] Both types are rich in methane content, compared to lignite coal. According to the EIA, Pennsylvania uses 38.3% of its coal to produce power, 12.5% to produce coke, 1.1% for other industrial uses, and the remaining 48% is exported. Overall, Strategen estimates that 80% of coal produced in the commonwealth is used for power generation, and 20% is used in the industrial sector.[96]

Strategen estimates that the coal mining subsector emitted 14.3 $MMTCO_2e$ in 2019, accounting for 16.6% of industrial emissions in Pennsylvania. The large majority, 11.9 $MMTCO_2e$, are fugitive emissions as reported in the GHG Inventory, while the remaining 2.4 $MMTCO_2e$ are estimated to come from fossil fuel combustion.

Fugitive emissions from coal, or coal mine methane emissions (CMM), are the second largest source of methane emissions in Pennsylvania. These are emitted from methane working through ventilation systems and gas drainage systems, post-mining activities such as processing, storage and transport, and abandoned mines. Emissions tend to be higher in underground mine operations than in surface mines, as deeper coal seams tend to contain more methane. In Pennsylvania, about 91% of the subsector's methane emissions are attributed to underground mining operations, with 3% to surface mines, and 6% to abandoned mines. At underground coal mines, ventilation air methane is the largest source of CMM, while drainage systems are a major source of emissions at surface mines.

Currently, there are available technologies to reduce fugitive emissions from coal mines, most of which are based on either flaring or capturing and utilizing the gas. Notably, both methods become more cost effective as the value of methane and emissions taxes increase.[97] Nonetheless, the most effective way to lower emissions

95 EIA, *Annual Coal Report*, 2023.

96 Pennsylvania is a producer of high rank coal which is better suited for industrial applications but also has a higher content of methane. Strategen used EIA data to approximate the share of coal production used in each subsector. At the national level, 92% of the coal production is used for power generation, 3% for coke production, and 5% for other industrial processes.

97 CMM can be used in many ways, including power generation, combined heat and power generation, sale to natural gas pipelines, coal drying, heat source for mine ventilation air, supplemental fuel for mine boilers, vehicle fuel as compressed or liquefied natural gas (LNG), and manufacturing feedstock.

from this subsector is to reduce the demand for coal, which would in turn decrease production. The business-as-usual scenario developed for this report considers an overall decrease in coal mining driven by expected changes in demand from the power and industrial sectors.

Given the reliance of the coal industry on demand from the power sector, this subsector is expected to be heavily impacted by advancements in the clean energy industry. Strategen's analysis assumes that the use of coal for the generation of electricity will be phased out by 2050, which translates to a 90% reduction in coal demand from the power sector. Meanwhile, baseline coal demand from the industrial sector is projected to increase commensurate with the rate of growth in each sector, absent interventions such as the solutions presented in Strategen's decarbonization pathway. Assuming no increases in international export levels, both trends result in base case coal production decreasing by 67% from 2019 levels by 2050, with the industrial sector representing three quarters of the coal demand by that year.

Decarbonization Pathway

Importantly, Strategen's decarbonization pathway for the coal mining subsector includes a reduction in coal demand resulting from the adoption of decarbonization levers across the other industrial subsectors, as suggested in this roadmap. The implementation of those pathway solutions will cut coal demand from the state's industrial sector in half by 2050. This reduction, combined with the impact of power sector decarbonization, would lead to a 77% to 81% decrease in production by 2050, depending on industrial coal demand from outside of the state. These demand reductions alone would result in lowering coal sector emissions by approximately 80% by 2050, if emissions from abandoned mines are successfully managed by local regulation and federal programs.

Further emission reductions are possible through the adoption of CMM management technologies. The IEA estimates that existing technologies are capable of avoiding over half of CMM emissions.[98] If those technologies are adopted in the state by 2050, regardless of cost and not assuming the emergence of new or improved technology, the emissions of the sector can be reduced by 90% by 2050.

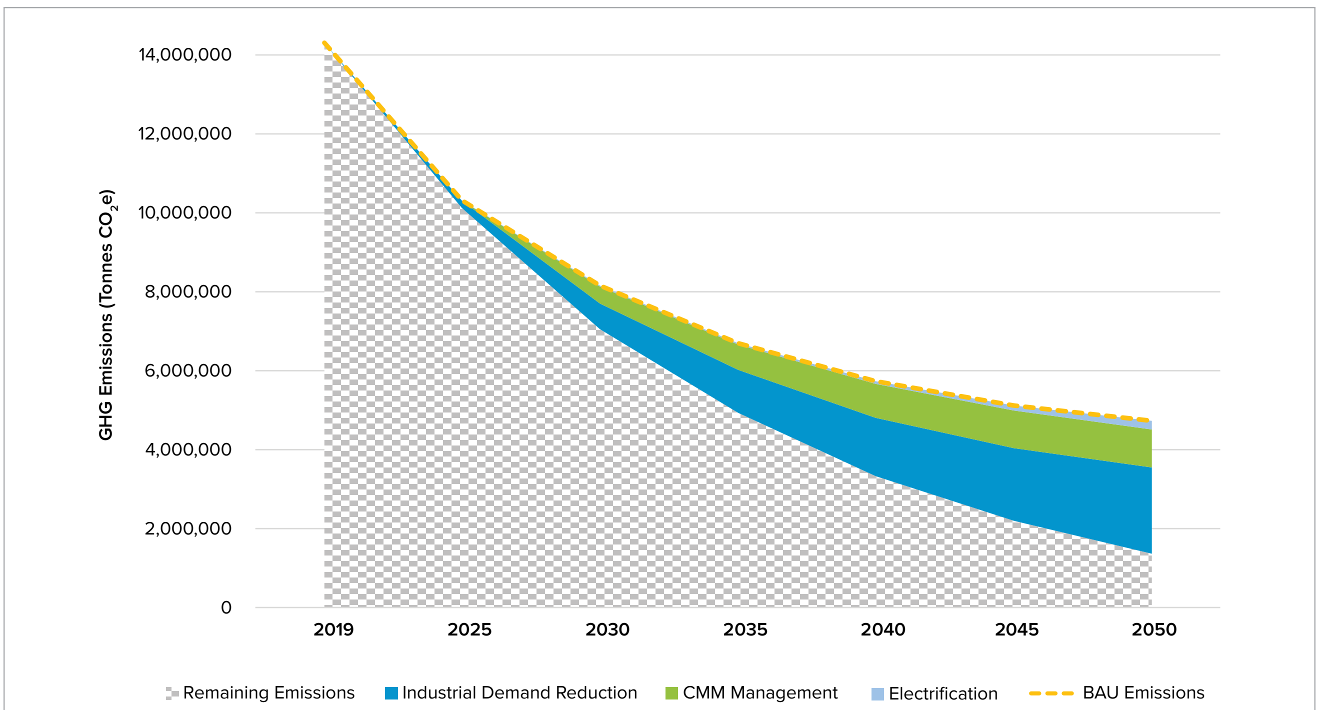


FIGURE 10: Projected Emissions Reductions in the Coal Mining Subsector (2019-2050)

98 IEA, "Global Methane Tracker 2023: Strategies to Reduce Emissions from Coal Supply," Accessed October 17, 2023. https://www.iea.org/reports/global-methane-tracker-2023/strategies-to-reduce-emissions-from-coal-supply.

Existing technologies to abate CMM emissions include methane capture from degasification systems prior to the start of mining operations, ventilation air systems (VAM) and drainage systems at working underground mines, and methane destruction methods like the use of flares or thermal oxidation. According to IEA, VAM capture could reduce CMM by 30%, but the low concentration of methane in VAM makes it costly to utilize or destroy the contained methane.[99] Methane drainage technologies can be used both prior to and post mine operations, generally utilizing a gas gathering system consisting of pipelines and vacuum pumps to extract gas to the surface. This gas contains higher methane concentrations, allowing for more effective extraction. Since the volume and concentration of methane flowing from coal mines is variable, capture and utilization technologies must be complemented with methane destruction systems such as flares and thermal oxidation for gas with lower methane concentration.

Abandoned coal mines can also produce significant methane emissions from diffuse vents, fissures, or boreholes for many years after mining ceases. In Pennsylvania, these represent only 6% of the subsector's fugitive emissions, but considering the pace of anticipated declines in coal demand and production, this share could increase rapidly. As part of the IIJA, Congress appropriated $11.3 billion for the Abandoned Mine Land (AML) grant program to remediate most of the currently known coal AML sites throughout the country.[100] Efficiency improvements for flares, gas engines, and related combustion equipment can further reduce CO_2 emissions from the subsector.

Portfolio Cost

The decarbonization pathway for coal will cost $128 million, with the majority of costs towards electrification. The cost of implementing CMM management and mitigation measures varies, based on mine characteristics, such as the type, scale, and location of each mine, as well as emissions volumes and methane concentration, which also vary during the life of a coal mine. Often, a small number of mines are responsible for an outsized level of emissions, and these can be abated more effectively through economies of scale. For these reasons, the EPA's Coalbed Methane Outreach Program (CMOP) provides stakeholders with tools and resources to enable profitable methane reductions. Since beginning in 1994, it has avoided close to 235 $MMTCO_2e$ in the United States, and the program currently identifies 10 potential projects for economic gas recovery in Pennsylvania.[101] In the commonwealth, CMM is listed as an alternative source of energy and can generate Renewable Energy Credits that can be traded to improve project economics.

The IEA's 2023 Global Methane Tracker estimates the cost of methane abatement with current technologies and shows that even without economic or tax incentives, it is cost-effective to recover almost 30% of abatable CMM, or 15% of total CMM emissions considering that half of emissions can be mitigated with existing technology. Strategen modeled these economic reductions taking place from 2025 to 2035, considering the steep reduction in production assumed to occur during those years. The remaining emissions reductions are modeled to increase linearly, starting in 2035 and achieving 50% abatement of total CMM emissions by 2050. The prices of CMM abatement in the analysis used the distribution shown in *Figure 11*, and averaged $9.2 per metric ton of CO_2e abated, based on information compiled by the UN Environment Program (UNEP).[102] Accelerating this timeline would require a steep decline in mitigation costs or the establishment of greater incentives to adopt available technologies or to mine coal seams with lower methane concentrations.

99 Available options for the use of VAM methane include regenerative thermal oxidation (using VAM at less than 2% methane concentrations as primary fuel), catalytic oxidation, lean-fuel turbines, and as a supplemental fuel for internal combustion engine turbines.
100 Public Law 117-58, November 15, 2021. https://www.congress.gov/117/plaws/publ58/PLAW-117publ58.pdf.
101 EPA, "Map of US Coal Mine Methane Current Projects and Potential Opportunities," Last modified November 17, 2023. https://www.epa.gov/cmop/map-us-coal-mine-methane-current-projects-and-potential-opportunities.
102 UNEP, Global Methane Assessment.

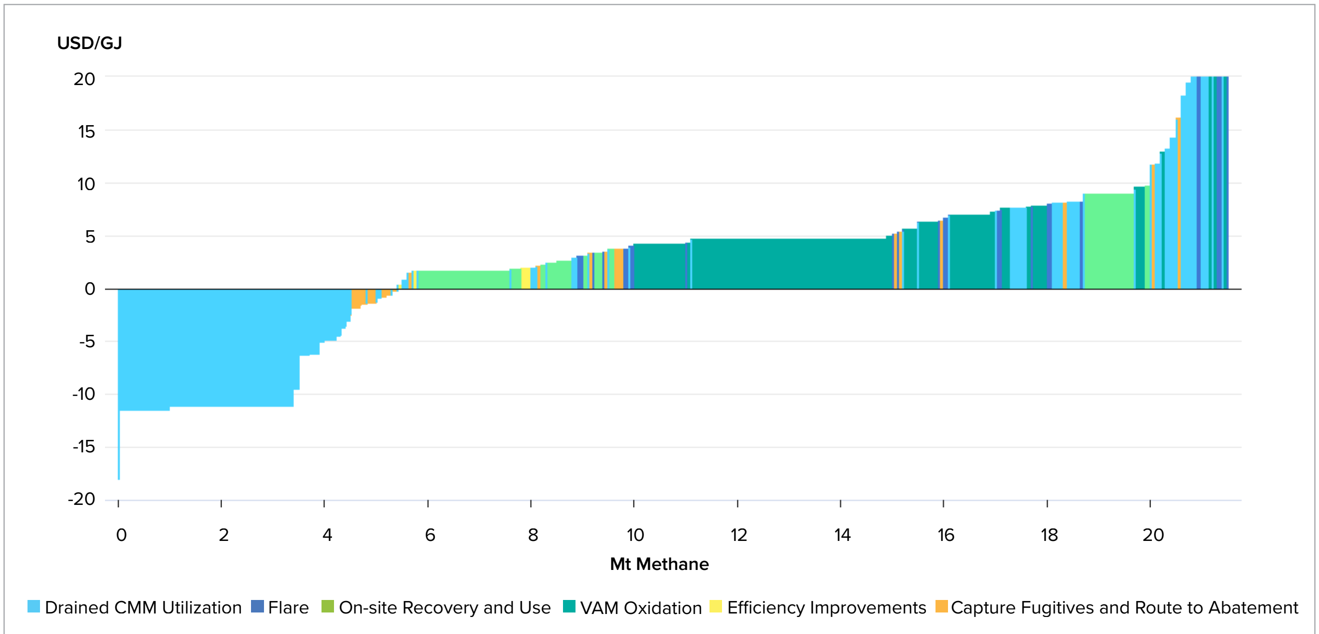


FIGURE 11: IEA's Methane Marginal Abatement Cost Curve for Coal Mine Emissions, 2022 | *Source: International Energy Agency*

Iron and Steel

Steel is an integral component of our built environment, but it is also a highly emissions intensive material. In Pennsylvania, iron and steel is responsible for 10.9% of annual industrial GHG emissions. Pennsylvania produced approximately 5.2 MMT of crude steel in 2019,[103] 55% of which was created using a blast furnace-basic oxygen furnace (BF-BOF) system, the most emission intensive method of steelmaking. There is only one such integrated facility in Pennsylvania, U.S. Steel's Mon Valley Works in Allegheny County, which is responsible for 71% of steelmaking emissions in the commonwealth. The operation consists of the Clairton coal coking plant, two downstream steel fabrication facilities, and the Edgar Thomson Plant, the BF-BOF facility generating the majority of Mon Valley's emissions.

The other 45% of the commonwealth's steel is produced through secondary steelmaking with electric arc furnaces (EAFs), mainly using recycled scrap steel. This breakdown is in opposition to production ratios throughout the rest of the world, where about 75% of steel is produced through BF-BOF. It also diverges from the United States steel industry, for which 67% is secondary steelmaking and 33% is primary steelmaking. Pennsylvania's steel industry is thus significantly less carbon intensive than the global average, but more carbon intensive than the U.S. average.

Notably, in 2021 U.S. Steel announced goals of achieving 20% reduced GHG emissions intensity by 2030 and net-zero GHG emissions by 2050.[104] Shortly after, the company canceled a $1 billion investment in Edgar Thomson and shut down three of the ten coking ovens at the Mon Valley Works coking facility, indicating a decreased interest in continuing to invest in coal-fired steelmaking and an opportunity for transition to cleaner manufacturing technologies.[105]

Most of the emissions from integrated steel mills come from the use of coal as a key feedstock. In the BF-BOF process, metallurgical coal is heated in coke ovens for up to 18 hours at high temperatures between 900 and 1,100° Celsius to produce a highly concentrated form of carbon called coke. The coke is then fed alongside iron ore into a blast furnace and blasted with hot air to create the high temperatures needed for reduction. In the blast furnace, the hot air ignites the coke, producing additional heat and carbon monoxide gas. The high heat, reaching

103 DOE, *Industrial Decarbonization Roadmap*; The U.S. steel industry produced 87 million MT of crude steel in 2018, and Pennsylvania is responsible for 6% of U.S. crude steel production.
104 U.S. Steel, "Roadmap to 2050," Accessed October 18, 2023. https://www.ussteel.com/roadmap-to-2050.
105 Jusko, J., "US Steel Cancels $1 Billion Mon Valley Works Project," Industry Week, May 3, 2021. https://www.industryweek.com/operations/article/21162960/us-steel-cancels-1-billion-mon-valley-works-investment.

temperatures up to 1,600° Celsius, melts the materials, and the gas acts as a reducing agent, stripping oxygen from the iron oxide to make molten pig iron.[106] The blast furnace process is a major source of GHG emissions (around 70%) as the oxygen combined with carbon is emitted as CO_2, along with the combustion of coal or natural gas to generate the high temperatures necessary for reduction.[107] The molten pig iron is then transferred to a basic oxygen furnace, where it is blown with oxygen to burn off unwanted impurities and refine the carbon content to convert it into steel.

Nearly half of steel production in Pennsylvania is secondary steel, using mostly scrap steel in an EAF, also known as a mini-mill. In this process, scrap steel, lime, and coal[108] are combined with small amounts of blast furnace-produced pig iron in the furnace, heated at up to 1,600° Celsius, and lanced with oxygen to remove impurities and produce liquid steel. This process is significantly less carbon intensive than BF-BOF steelmaking, with 80% fewer GHG emissions.[109] The emissions from secondary steelmaking come from small amounts of fossil combustion to provide initial heat, oxygen lancing, and the process emissions from lime, coal, and steel contaminants.[110]

Following the production of crude steel, the liquid metal is cast, often transferred to a reheat furnace, and put through a number of possible fabrication processes, such as hot-rolling, annealing, and galvanizing. These are primarily high heat processes that use natural gas combustion, and this step of the steelmaking process accounts for approximately 20% of emissions from the sector.

Consistent with the DOE's *Industrial Decarbonization Roadmap*, demand for iron and steel is assumed to increase 12% overall by 2050.[111]

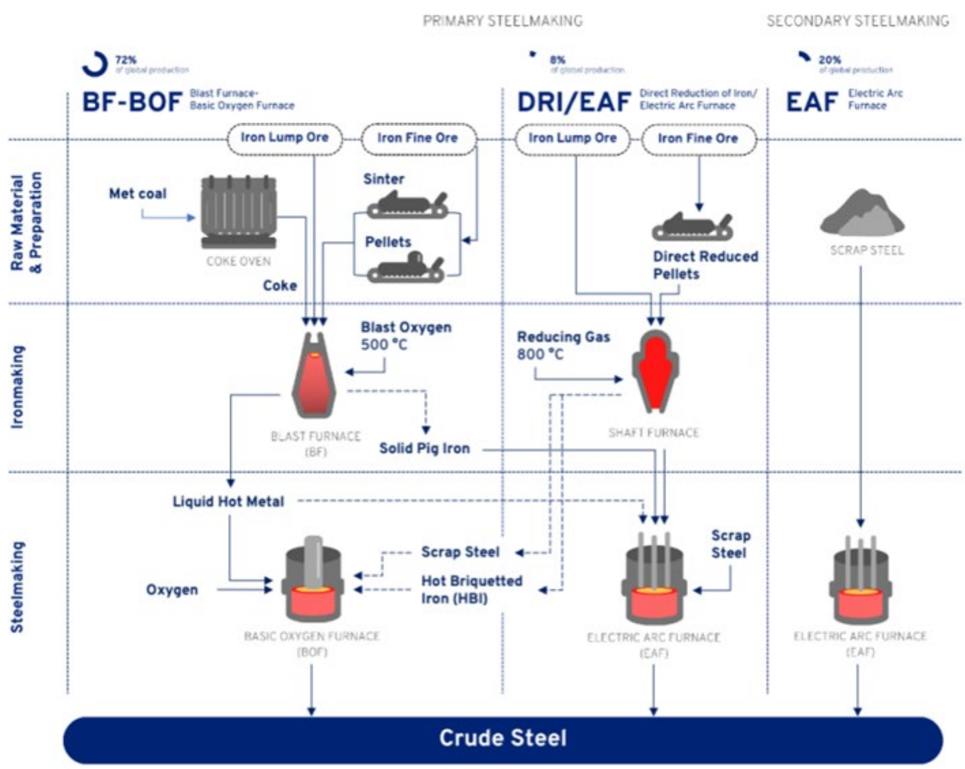


FIGURE 12: Primary and Secondary Steelmaking Process | *Source: Ohio River Valley Institute, 2023.*

106 Kim, J. et al., *Decarbonizing the Iron and Steel Industry: A Systematic Review of Sociotechnical Systems, Technological Innovations, and Policy Options*, Energy Research and Social Science, July 2022. https://doi.org/10.1016/j.erss.2022.102565. (Hereafter "Kim, J. et al., *Decarbonizing the Iron and Steel Industry*").
107 Fan, Z. and Freidmann, S. J., *Low-Carbon Production of Iron and Steel: Technology Options, Economic Assessment, and Policy*, Joule, April 2021. https://doi.org/10.1016/j.joule.2021.02.018. (Hereafter "Fan, Z. and Freidmann, S. J., Low-Carbon Production of Iron and Steel").
108 Lime acts as a fluxing agent while coal acts as foaming agent for slag.
109 Kim, J. et al., Decarbonizing the Iron and Steel Industry.
110 Wiley, D., Ho. M. and Bustamante, A., *Assessment of Opportunities for CO_2 Capture at Iron and Steel Mills: An Australian Perspective, Energy Procedia, 2011*. https://doi.org/10.1016/j.egypro.2011.02.165.
111 DOE, Industrial Decarbonization Roadmap.

Decarbonization Pathway

The solutions employed to decarbonize the steelmaking subsector include efficiency, fuel switching to hydrogen, electrification, and CCS.

Strategen's decarbonization pathway assumes that efficiency measures can lead to a 20% reduction in primary steelmaking CO_2e emissions by 2035, taking advantage of commercially available technologies and demand reduction methods to improve efficiency in energy and material use, as well as production. It also includes technologies like oxy-fuel burners,[112] waste heat recovery, and continuous casting. This reduction is in line with EIA's Sustainable Development Scenario.[113]

Increased recycling and deployment of secondary steelmaking EAF mini-mills is an available technology solution today. Scrap EAF steel production is significantly less carbon intensive than traditional primary steelmaking, but its growth and decarbonization potential is limited by scrap availability and the demand for primary steel. The scrap recycling rate for steel in the U.S. is already between 80% and 90%[114] and certain products require a grade of steel that only primary production can supply.[115] However, there is still room for modest improvement, and scrap EAF accounts for a 10% reduction in primary steelmaking emissions by 2050 in Strategen's pathway.

While primary steelmaking today almost exclusively uses coal and blast furnace technology, it can alternatively be performed with direct reduced iron (DRI), which uses natural gas as a reductant in a shaft furnace rather than coal in a blast furnace, and an electric arc furnace rather than a fossil fuel-fired basic oxygen furnace. This process (DRI-EAF) is roughly 38% less emission intensive than the BF-BOF method.[116] Currently, there are no DRI-EAF facilities in Pennsylvania, but the technology is commercially available and has already been successfully deployed in the United States, with Cleveland Cliffs starting production at its new Toledo DRI plant in 2020.[117] Further, the United States is home to the leading shaft furnace producer in the world, North Carolina-based Midrex Technologies. A key limitation for DRI, however, is that it requires a higher quality iron ore (DR-grade) than that used in a blast furnace. While supply for DR-grade iron ore may be tight, there are significant ongoing investments to ramp up supply and innovations to upgrade lower grade iron ore in the face of increasing demand. U.S. Steel broke ground in 2022 on Minnesota mining facilities that will produce pellets that can be converted to DRI,[118] and Champion Iron in Quebec is examining opening a new mine that will add up to 8 million metric tons per year in additional DR-grade iron ore mining capacity.[119] Fuel switching to natural gas DRI is a key intermediate solution in lowering emissions associated with primary steelmaking. While not modeled as a onetime switch, it is assumed Strategen's pathway that the majority (90%) of primary production, and resulting emissions, is shifted to DRI technology by 2050.

The DRI-EAF process provides an additional opportunity for the decarbonization of primary steelmaking. With current technology, DRI is performed using a natural gas product called syngas, a mixture of carbon monoxide (CO) and hydrogen. However, DRI shaft furnaces can shift to using 100% hydrogen with minor retrofit or can be designed and built specifically for hydrogen-based reduction.[120,121] The use of clean hydrogen as a reductant, paired with an electric arc furnace powered by renewable electricity is a technically feasible and viable option

112 In addition to improving energy efficiency, using oxy-fuel burners allows the full replacement of natural gas with clean hydrogen as fuel with minimal retrofit.
113 Budinis, S. et al., *Iron and Steel Technology Roadmap: Towards More Sustainable Steelmaking*, IEA, 2020. https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf.
114 Tuck, C. T., "Iron and Steel Scrap Mineral Commodity Summary," U.S. Geological Survey, 2021. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-iron-steel-scrap.pdf.
115 Cooper, D.R. et al., *The Potential for Material Circularity and Independence in the U.S. Steel Sector*, Journal of Industrial Ecology, January 2020. https://doi.org/10.1111/jiec.12971.
116 Fan, Z. and Freidmann, S. J., Low-Carbon Production of Iron and Steel.
117 Cleveland Cliffs, "Toledo Direct Reduction Plant Fact Sheet," Last modified March 2023. https://d1io3yog0oux5.cloudfront.net/_693fc1c48d410baacd70c0cfd2cdf933/clevelandcliffs/db/1170/10171/fact_sheet/CLF_FactSheet_DRPlant_032023.pdf.
118 Taylor, B., "US Steel Turns to DRI and Pig Iron for EAFs," Recycling Today, June 28, 2022. https://www.recyclingtoday.com/news/us-steel-pig-iron-dri-not-recycling/.
119 Crux Investor, "Champion Iron Looks to Tap into Growing Demand for High-Grade Iron Ore," October 2, 2023. https://www.cruxinvestor.com/posts/champion-iron-looks-to-tap-into-growing-demand-for-high-grade-iron-ore.
120 Fan, Z. and Freidmann, S. J., Low-Carbon Production of Iron and Steel.
121 Rothberger, J. et al., "The Winding Road Toward Zero-Carbon Iron," Midrex Technologies, December 2021. https://www.midrex.com/tech-article/the-winding-road-toward-zero-carbon-iron/.

for zero-emission primary steel production. This technology has seen the most traction, development, and investment in the pursuit of clean steel thus far, with a number of successful demonstration projects and planned commercial operations in Europe. Liberty Steel Group is building a DRI plant in Romania that will initially use natural gas before transitioning to clean hydrogen with the goal of reaching carbon neutrality by 2030. Last year, plans were put in place to replace a blast furnace at Germany's largest steelmaking plant with a 2.5 MMT capacity DRI plant that will begin production using hydrogen in 2026.[122] The United States is behind Europe, but the technology may soon come to North American shores as Swedish company H2 Green Steel is in talks with governments in Canada to build a factory in northern Quebec. There is increasing demand in America for clean steel, as Microsoft, Trammell Crow, and Nextracker announced a plan in 2023 to jointly request 2 MMT of "near-zero emissions" steel to push North American steelmakers to adopt greener manufacturing methods.[123] In Strategen's pathway, most of the production from DRI in the near- to medium-term uses natural gas, but by 2050 75% of steel using DRI is transitioned or built to use clean hydrogen.

Another option for decarbonization is through CCS. BF-BOF facilities are not particularly suitable for carbon capture because there are many different emission points and low flue gas CO_2 concentrations. However, natural gas-based DRI is better suited for capture technologies as it generates flue gas streams with CO_2 concentrations up to 90%. There are near-term plans in America for DRI with CCS, as a DRI plant in Louisiana is on track to install carbon capture technology on the facility in 2026 that is expected to capture 800,000 metric tons per year of CO_2.[124] In Strategen's pathway it is assumed that 25 % of steel using DRI is retrofit or built with CCS. However, is assumed to only capture and reduce 90% of emissions, reflecting its technological limitations.

A longer-term solution for primary steelmaking is through electrification. Direct electrolysis of iron ore has been demonstrated in lab settings and is in the early stages of development, but has not been proven and is not expected to be available commercially until at least 2040.[125] While this technology could be transformative in the steel industry, it was not included in this pathway due to its low maturity and lack of available cost estimates.

Although secondary steelmaking though the EAF is already far less carbon intensive than primary steelmaking, there are still emissions from these facilities that need to be abated, namely from emissions from initial fossil fuel combustion as a startup boost and process emissions from chemical reactions in the furnace. Efficiency-related reductions of 33% by 2050 are assumed for combustion emissions, based on the potential for process improvements, energy efficiency measures, and scrap densification.[126] Process emissions come from the use of lime as a fluxing agent and small amounts of coal as a carbon source and foaming agent. Char, from biomass such as saw dust and corn stalk, has been shown to be a suitable substitute for a portion of these material, and represents a 50% reduction in remaining emissions.[127]

Steel fabrication uses high and medium-temperature heat generated by the combustion of fossil fuels (mainly natural gas) to cast, reheat, treat, roll, and anneal semi-finished steel. There are a number of efficiency solutions that can be applied to these processes, such as waste heat recovery, continuous casting, and oxyfuel burner retrofit. Efficiency-related reductions of 20% by 2050 are assumed for fabrication. Oxyfuel burner retrofits, which use oxygen rather than air as the primary oxidizer in combustion, have the added benefit of allowing for

122 Thyssenkrupp, "Thyssenkrupp Is Accelerating the Green Transformation: Decision Taken on the Construction of Germany's Largest Direct Reduction Plant for Low-CO_2 Steel," September 8, 2022. https://www.thyssenkrupp.com/en/newsroom/press-releases/pressdetailpage/thyssenkrupp-is-accelerating-the-green-transformation--decision-taken-on-the-construction-of-germanys-largest-direct-reduction-plant-for-low-CO2-steel-146809.

123 Gallucci, M., "Major Steel Users Band Together to Place First Big 'Green Steel' Order," Canary Media, September 20, 2023. https://www.canarymedia.com/articles/clean-industry/major-steel-users-band-together-to-place-first-big-green-steel-order.

124 Nucor, "Nucor Enters into Carbon Capture & Storage Agreement with ExxonMobil," June 1, 2023. https://nucor.com/news-release/19816.

125 Ito, A., Langefeld, B. and Gotz, N., *The Future of Steelmaking — How the European Steel Industry Can Achieve Carbon Neutrality*, Roland Berger, 2020. https://www.rolandberger.com/publications/publication_pdf/rroland_berger_future_of_steelmaking.pdf.

126 Jamison, K. et al., Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing, DOE, 2015. https://www.energy.gov/sites/prod/files/2015/08/f26/iron_and_steel_bandwidth_report_0.pdf.

127 Kieush, L. et al., *Utilization of Renewable Carbon in Electric Arc Furnace-Based Steel Production: Comparative Evaluation of Properties of Conventional and Non-Conventional Carbon-Bearing Sources*, Metals, January 2023. https://doi.org/10.3390/met13040722.

fuel switching from natural gas to clean hydrogen with minimal retrofit.[128] Fuel switching to hydrogen for high temperature combustion in reheat furnaces has been successfully demonstrated by Swedish company Linde, which showed in 2020 that 100% hydrogen fuel use did not have any adverse impacts on the steel's quality.[129] In Strategen's pathway, it is assumed that fuel switching to hydrogen accounts for 60% of fabrication emission reductions after efficiency improvements. Certain low and medium-temperature processes may be able to be electrified through the use electric boilers, heat pumps, and electric reheat furnaces.[130,131]

Using this combination of solutions CO_2e emissions from Pennsylvania's iron and steel industry can be reduced 19% by 2030 and 92% by 2050.

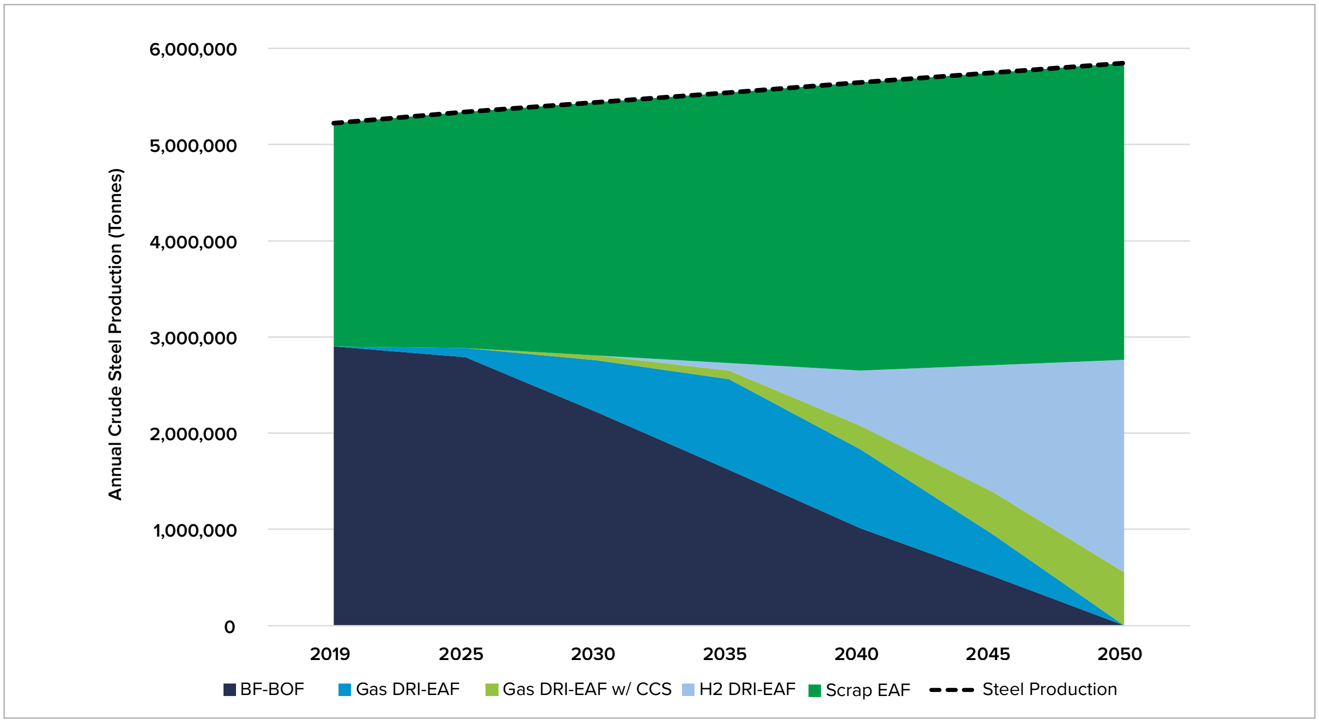


FIGURE 13: Pennsylvania Steel Production (tons of crude steel)

128 Von Scheele, J., *Embracing Hydrogen Flameless Oxyfuel for CO_2-Free Heating*, Iron and Steel Today, 2020. https://www.lindehydrogen.com/-/media/corporate/linde-hydrogen/files/brochures_downloads/ist_linde_editorial_v2-(1).pdf?la=en.

129 Ibid.

130 Schmitz, N. et al., *Towards CO_2-Neutral Process Heat Generation for Continuous Reheating Furnaces in Steel Hot Rolling Mills – A Case Study*, Energy, June 2021. https://doi.org/10.1016/j.energy.2021.120155.

131 DOE, Industrial Decarbonization Roadmap.

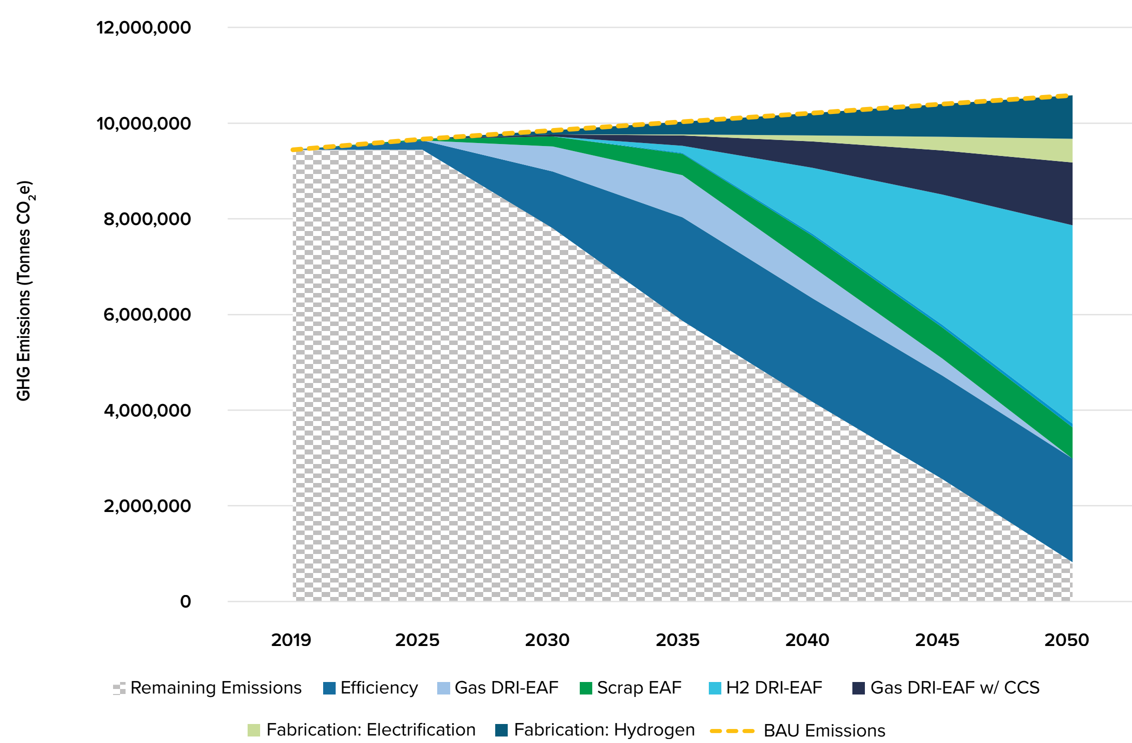


FIGURE 14: Iron and Steel Manufacturing Decarbonization Pathway (2019-2050)

Portfolio Cost

This decarbonization pathway for steel would require 207,891 tons of hydrogen per year and would cost $2.3 billion to reduce emissions 19% by 2030 and 92% by 2050. Hydrogen DRI costs are based on Hydrogen Europe's capital cost estimates for replacing an integrated steel plant with a DRI-EAF facility, inclusive of brownfield conversion costs and were estimated by Strategen to total approximately $917 million for facilities in Pennsylvania.[132] Costs for scrap EAF facilities and DRI with CCS are $65 million and $1.1 billion respectively, and were sourced from DOE's *Pathway to Commercial Liftoff for Industrial Decarbonization* report and costs reported by the Energy Futures Initiative.[133] Fuel switching and electrification costs for fabrication were sourced from Element Energy and LBNL respectively.[134]

Key Takeaways

+ The iron and steel subsector is responsible for 10.9% of annual industrial emissions in Pennsylvania.
+ 55% of production is primary steelmaking using coal in a blast furnace while 45% is secondary steelmaking using recycled scrap steel in an electric arc furnace.
+ The following solutions can be utilized to reduce subsector emissions 19% by 2030 and 92% by 2050:
  – A 20% more efficient subsector is assumed for primary steelmaking and fabrication and a 33% more efficient subsector is assumed for secondary steelmaking.
  – Increasing steel recycling and usage of electric arc furnaces is limited by the high existing recycling rate and primary steel needs, but still shifts 10% of primary steel demand by 2050.

132 Pawelec, G. and Fonseca, J., *Steel from Solar Energy: A Technoeconomic Assessment of Green Steel Manufacturing*, Hydrogen Europe, 2022. https://hydrogeneurope.eu/wp-content/uploads/2022/06/Steel_from_Solar_Energy_Report_05-2022_DIGITAL.pdf.
133 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization; Energy Futures Initiative, 2023. *Turning CCS projects in heavy industry and power into blue chip financial investments*. https://efifoundation.org/wp-content/uploads/sites/3/2023/02/20230212-CCS-Final_Full-copy.pdf. (Hereafter "EFI CCS 2023").
134 Durusut, E. et al., *Conversion of Industrial Heating Equipment to Hydrogen*, Hy4Heat, 2019. https://www.hy4heat.info/wp6. (Hereafter "Durusut, E. et al., Conversion of Industrial Heating Equipment")

- 90% of primary steel production shifts to DRI-EAF, initially using natural gas, but by 2050 75% of DRI uses clean hydrogen and 25% is retrofit with CCS.
- Emissions from secondary steelmaking are reduced 50% by replacing coal and lime with biochar.
- Emissions from downstream steel fabrication are reduced from a combination of clean hydrogen and electrification.

+ The implementation of this portfolio of solutions will cost $2.3 billion in aggregate.

Other Metals

In addition to steel production, there are a number of industrial facilities in Pennsylvania that produce or handle various metals. These include aluminum, zinc, lead, and certain standalone downstream steel fabrication facilities. Initial manufacturing of these metals in Pennsylvania is primarily performed using recycled and scrap materials rather than through primary production, but most of the facilities in this category are dedicated to metal processing into sheets, extrusions, and other fabrications. These facilities share similar emissions profiles, driven primarily by high temperature process heat from the combustion of fossil fuels.

Primary or secondary production of other metals typically involves high temperature furnaces and smelters. The majority of emissions and energy from this category in Pennsylvania, however, come from the downstream process, which involves varied stages, but typically begins with scrap or primary metal being fed into a reheat or melting furnace at high temperatures, usually fueled by natural gas combustion. Following this initial stage, metals may be put through a number of possible fabrication processes such as hot rolling, extruding, brazing, stamping, annealing, and galvanizing. Certain low and medium-temperature processes may be involved such as treating, cooling, and finishing.

Decarbonization Pathway

Energy efficiency solutions such as waste heat recovery and oxyfuel combustion are available and cost-effective in the near term. Adoption of oxyfuel solutions, in particular, can provide significant reduction potential as both an efficiency solution and an enabling technology for combusting 100% hydrogen.[135] Material efficiency, using less material to make the same products, has significant potential to reduce emissions. Researchers at the University of Cambridge found that “we could use 30 percent less metal than we do at present, with no change in the level of material service provided, simply by optimizing product design and controlling the loads that they experience before and during use.”[136] By 2050, it is expected that efficiency measures can decarbonize approximately 20% of metals emissions.

Given that most emissions from this sector are from fossil fuel combustion, fuel switching is an important decarbonization solution. Natural gas burners can be retrofit to combust clean hydrogen for high temperature processes. In Strategen’s pathway, high-temperature combustion emissions will be reduced by switching to clean hydrogen, while electrification using electric furnaces, boilers, and high temperature heat pumps will reduce emissions from low- and medium-temperature heating needs.

Utilizing this combination of solutions, Pennsylvania’s other metals sector can decarbonize 12% by 2030 and 90% by 2050.

135 As previously mentioned, oxyfuel technology using oxygen rather than air as an oxidizer can generate energy savings of 25-35%.
136 Rissman, J., *Decarbonizing Low-Temperature Industrial Heat in the U.S.*, Energy Innovation, 2022. https://energyinnovation.org/wp-content/uploads/2022/10/Decarbonizing-Low-Temperature-Industrial-Heat-In-The-U.S.-Report-1.pdf. (Hereafter “Rissman, J., Decarbonizing Low-Temperature Industrial Heat”).

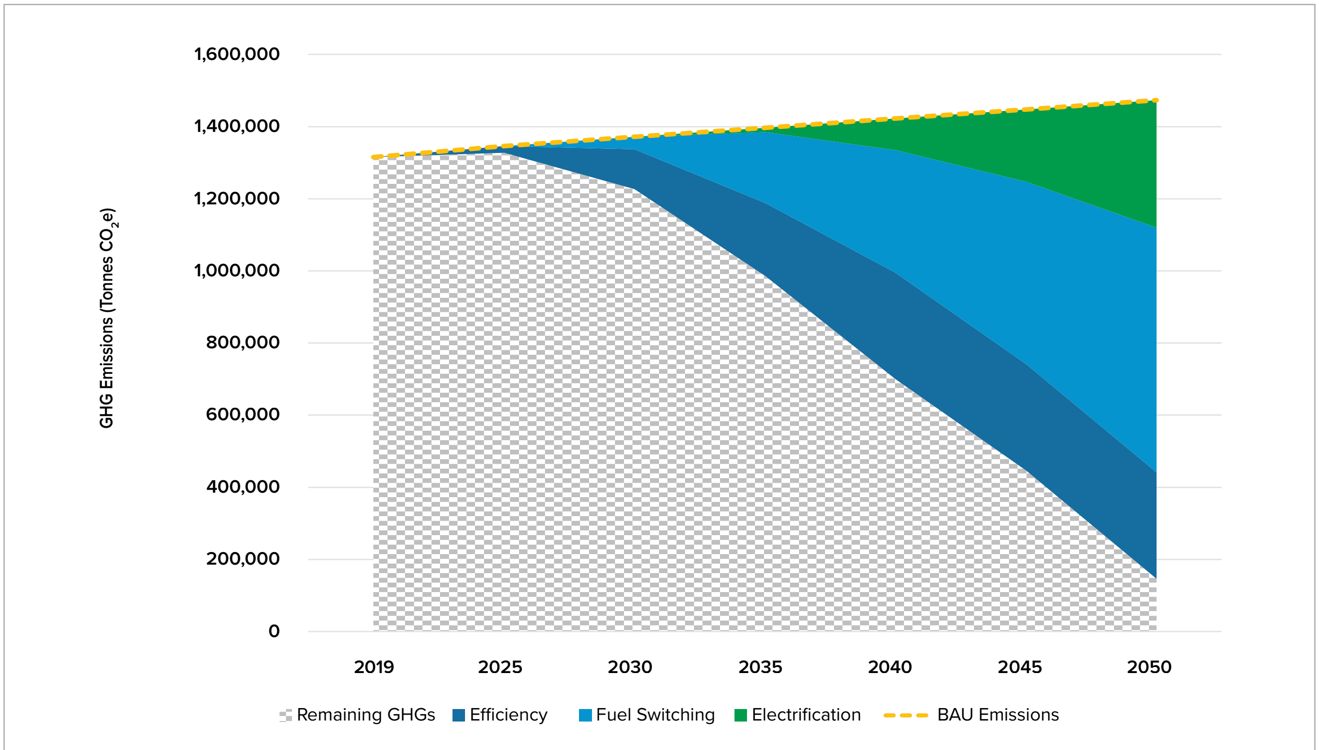


FIGURE 15: Other Metals Decarbonization Pathway (2019-2050)

Portfolio Cost

The implementation of this portfolio of solutions will cost $234 million in aggregate. It is assumed that the energy efficiency improvements applied for this sector will not require significant net expenditures over time and may even result in a positive return.[137] Fuel switching costs total $23 million based on estimates of the cost to convert a basic metals furnace from natural gas to operate on hydrogen.[138] Electrification costs were calculated based on process heat electrification costs from DOE, resulting in $210 million for this subsector.[139]

Key Takeaways

+ The other metals subsector is responsible for 1.5% of annual industrial emissions in Pennsylvania.
+ The subsector consists of a number of industrial facilities in Pennsylvania that produce or handle various metals, including aluminum, zinc, lead, and certain standalone downstream steel fabrication facilities.
+ The following solutions can be utilized to reduce glass subsector emissions 12% by 2030 and 92% by 2050:
  - Efficiency measures can eliminate approximately 20% of emissions.
  - Fuel switching to hydrogen for high-temperature processes is a significant decarbonization lever and is applied to 60% of emissions after efficiency by 2050.
  - Electrification of low- to medium-temperature processes covers 30% of emissions reductions after efficiency.
+ The implementation of this portfolio of solutions will cost $234 million in aggregate.

137 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.
138 Durusut, E. et al., Conversion of Industrial Heating Equipment.
139 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.

Minerals

This subsector encompasses both the production of cement and lime as well as the use of naturally occurring limestone and dolomite in other industrial processes. Combined, these applications are responsible for approximately 5.9% of annual industrial emissions in Pennsylvania.[140] Specifically, cement production is responsible for 3.5% of total industrial emissions, lime manufacturing is responsible for 1.4%, and the use of limestone and dolomite accounts for the remainder. With annual production of ~4,000 metric tons, Pennsylvania is a leading producer of cement in the US.[141]

About 60% of emissions from Pennsylvania's cement and lime industry in 2019 were from the combustion of fuels for process heat. A diversity of carbon intensive fuels is used in the production process of cement and lime, including natural gas, propane, and distillate fuel oil no. 2.[142] The remainder of emissions are process-related and are produced by the precalciner chemical reaction where CO_2 is formed through decomposition of the calcium/magnesium carbonates. All emissions from limestone and dolomite use are considered process emissions as they are naturally occurring minerals that are directly used in other industries.

Lime and cement are both types of binding material that bond together with aggregates such as sand to form a mortar that will harden and adhere to materials. While these materials have differences in curing time, cost, and compressive strength, their production processes and fuel use are nearly identical,[143] and thus have been combined in Strategen's analysis.

Cement and lime are manufactured in kilns according to the following reaction:

$$CaCO_3 + \text{Heat} \longrightarrow CO_2 + CaO$$

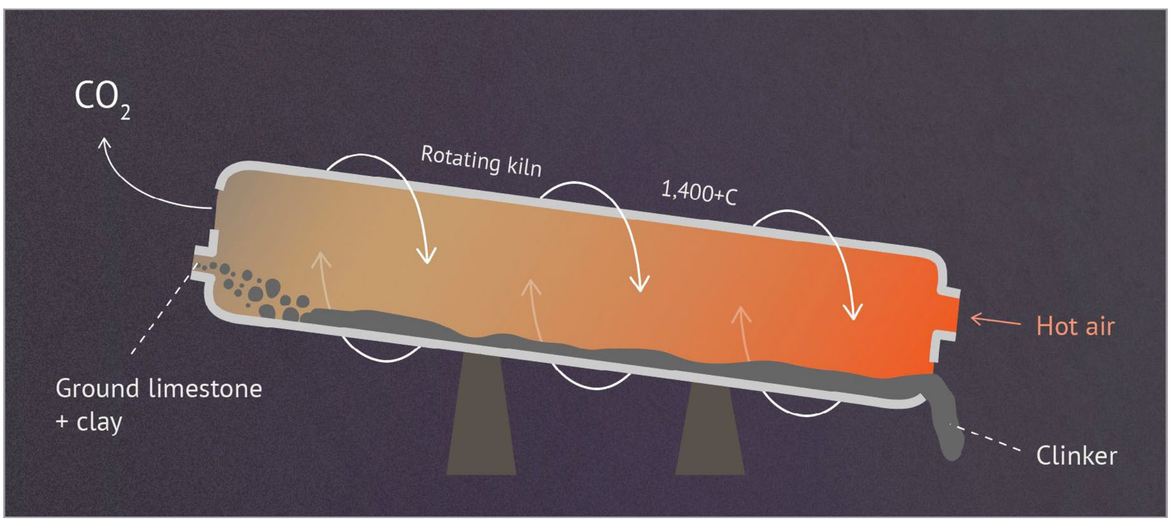


FIGURE 16: Visualization of the Cement and Lime Manufacturing Process | *Source: Carbon Brief*

Lime and cement production involves two major steps: the precalciner (600-700° Celsius) and the rotary kiln (1200-1400° Celsius) for clinker production.[144] The majority of emissions are from the precalciner, where CO_2 is released from the decomposition of the calcium/magnesium carbonates.

140 Pennsylvania GHG Inventory.
141 Portland Cement Association (PCA), Pennsylvania Cement Industry, 2016. https://www.cement.org/docs/default-source/ga-pdfs/cement-industry-by-state-2015/pennsylvania.pdf?sfvrsn=2&sfvrsn=2; Pennsylvania Aggregates and Concrete Association, "Our Industry: Overview," Accessed October 17, 2023. https://www.pacaweb.org/community/our-industry.
142 EPA, *Facility Level Information on GreenHouse gases Tool (FLIGHT)*. (Hereafter "EPA FLIGHT").
143 Stonehenge Masonry Company, "Lime vs Portland Cement? Which Is Better?," Accessed October 17, 2023. https://stonehengemasonry.ca/lime-vs-portland-cement-which-is-better.
144 Clinker is an intermediary material produced in the cement making process. It is discharged from the end of the kiln in the form of rocks that are 3-25 millimeter in diameter. After the clinker is cooled, cement plants grind it and mix it with small amounts of gypsum and limestone to produce cement.

Limestone ($Ca(CO_3)_2$) and dolomite ($CaMg(CO_3)_2$) are sedimentary rocks, specifically carbonates, that are quarried from open pits and underground mines and used for flux stone production, glass manufacturing, flue gas desulfurization (FGD), and other various uses.[145] For Strategen's analysis, the quantities of limestone and dolomite consumed for industrial purposes are multiplied by their respective emission factors to calculate overall process emissions.

A key challenge in reducing CO_2 emissions from the cement sector is the need to meet growing annual demand, particularly for construction. Demand for cement is expected to grow at approximately 1% per year through 2050, and demand for lime production and the use of limestone and dolomite was assumed to grow at the same rate as the demand for cement due to their overlapping use cases.[146]

Decarbonization Pathway

Decarbonization in the cement and lime production industry will necessitate a variety of solutions. Energy efficiency and fuel switching to clean hydrogen for high-temperature process heat can eliminate nearly all combustion-related emissions. By 2050, it is expected that efficiency measures can eliminate approximately 25% of annual cement and lime combustion emissions. [147] Although many gains have been made in the industry, there is still room for improvement in energy efficiency. Europe and the United States now lag behind India and China on energy efficiency, due to the continued use of older equipment.[148] Efficiency gains were assumed to begin in 2025 and increase linearly with time through 2050. Of note, switching from incumbent rotary kilns[149] to much more efficient parallel flow regenerative kilns (PFR)[150] offers significant energy efficiency improvements, however, because this energy efficiency improvement has a significant cost and may not be compatible with the installation of kilns that can operate on zero-carbon fuels, it was not included in Strategen's roadmap. Rather, energy efficiency improvements within this subsector are focused on waste heat recovery, smart energy management, improvements to fans and motors, and other lower capital-intensive improvements.

The remainder of combustion emissions will be reduced linearly by using clean hydrogen for high-temperature kiln process heat beginning in 2030.

Material substitution and process improvements can reduce cement process emissions by 40% by 2050.[151] Material substitution involves replacing a share of the clinker content in cement with other materials. Clinker substitution is not only a very effective solution, but also one that can be deployed cheaply today, as it does not require investments in new equipment or changes in fuel sources. Material efficiency improvements were assumed to kick off at the beginning of the decarbonization pathway in 2025 and increase linearly through 2050. The remainder of process emissions will be linearly reduced through CCS beginning in 2030. Specifically, regarding the use of lime and dolomite, all emissions are process emissions, so CCS will be required for decarbonization.

Utilizing this combination of solutions, emissions from Pennsylvania's minerals industry can be reduced by 9% by 2030 and 94% by 2050.

145 BCS, Incorporated, "Limestone and Crushed Rock," in Energy and Environmental Profile of the U.S. Mining Industry, 2002. https://www.energy.gov/sites/prod/files/2013/11/f4/stone.pdf.

146 PCA, *Roadmap to Carbon Neutrality*, 2021. https://www.cement.org/docs/default-source/membership-2020/pca_roadmap-to-carbon-neutrality_jan-2022.pdf. (Hereafter "PCA, Roadmap to Carbon Neutrality").

147 Ibid.; Vito and Climact, *A Low-Carbon Roadmap for Belgium: Industry Sector – Lime*, 2013. https://climat.be/doc/8-industry-lime.pdf.

148 Lehne, J. and Preston, F., *Making Concrete Change: Innovation in Low-Carbon Cement and Concrete*, Chatham House, 2018. https://www.chathamhouse.org/sites/default/files/publications/research/2018-06-13-making-concrete-change-cement-lehne-preston.pdf.

149 European Lime Association, *A Competitive and Efficient Lime Industry*, 2014. https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Summary_0.pdf.

150 Ibid.

151 PCA, Roadmap to Carbon Neutrality; Fennell, P., Davis, S. and Mohammed, A., *Decarbonizing Cement Production*, Joule, June 2021. https://doi.org/10.1016/j.joule.2021.04.011.

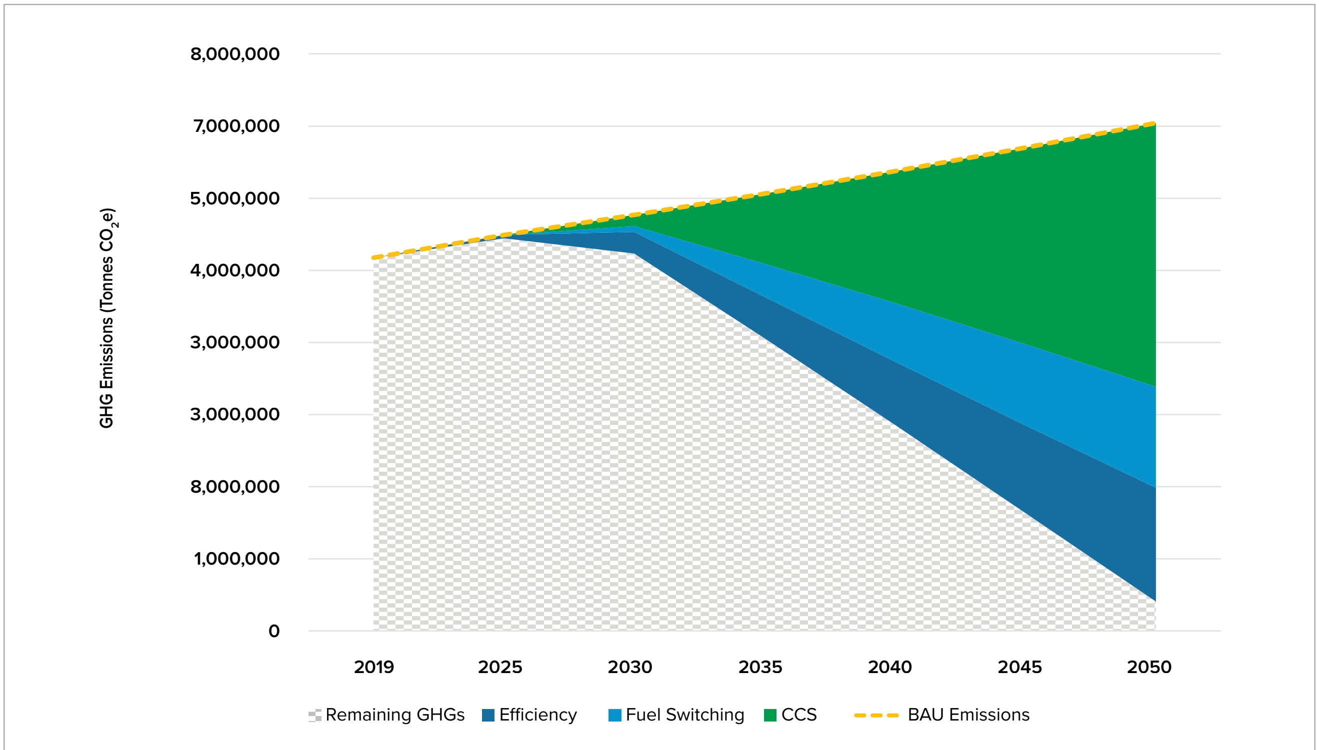


FIGURE 17: Minerals Decarbonization Pathway (2019-2050)

Portfolio Cost

The implementation of this portfolio of solutions will cost $8.7 billion, including $3.7 billion for fuel switching and $5 billion for CCS. It is assumed that energy efficiency improvements will ultimately not require significant capital expenditures over time and may even result in a positive return.[152]

Fuel switching costs are based on cost estimates produced by the DOE in its Pathways to Commercial Liftoff: Industrial Decarbonization Report.[154] Costs for CCS were sourced from the Energy Futures Initiative.[154]

Key Takeaways

+ The minerals subsector is responsible for 5.9% of annual industrial emissions in Pennsylvania. Specifically, cement production is responsible for 3.5% of total industrial emissions, lime manufacturing is responsible for 1.4%, and the use of limestone and dolomite accounts for the remainder.
+ For cement and lime manufacturing, 60% of emissions are from the combustion of fuels for process heat, and 40% are from the production reaction. All emissions from limestone and dolomite use are considered process emissions as they are naturally occurring minerals that are directly used in other industries.
+ The following solutions can be utilized to reduce mineral subsector emissions 9% by 2030 and 94% by 2050:
  – Energy efficiency measures can eliminate approximately 25% of annual cement and lime combustion emissions.
  – Fuel switching can decarbonize the remainder of combustion emissions.
  – Material substitution and process improvements can reduce cement process emissions by 40%.
  – The decarbonization of process emissions will require CCS.
+ The implementation of this portfolio of solutions will cost $8.7 billion in aggregate.

152 Goldman, S. et al., P*athways to Commercial Liftoff: Low-Carbon Cement*, DOE, 2023. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230921-Pathways-to-Commercial-Liftoff-Cement.pdf. (Hereafter "DOE, Pathways to Commercial Liftoff: Low-Carbon Cement").
153 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.
154 EFI CCS 2023.

Chemical Manufacturing

The chemical manufacturing subsector is responsible for about 3.4% of annual industrial emissions in Pennsylvania[155] and utilizes a variety of carbon-intensive fuels in the production process, including natural gas, propane, distillate fuel oil no. 2, and residual fuel oil no. 6.[156] Notably, Shell's ethylene cracker facility, located in Beaver County, which commenced operations in late 2022, makes up 66% of annual petrochemical sector emissions in Pennsylvania, assuming the facility operates at its maximum emissions allowance.[157]

The main chemical product manufactured in Pennsylvania is polyethylene, which is produced using a process called "cracking." Ethane cracking involves the application of intense heat (above 800° Celsius) to ethane, a component of natural gas, under controlled conditions to create ethylene. Ethylene is used as the basis for plastic products, such as beverage containers, food wrap, polyvinyl chloride, polyester, and chemicals like those found in antifreeze, solvents, urethanes, and pharmaceuticals. Pennsylvania also produces several other petrochemicals within smaller facilities at process heat temperatures ranging from around 100° Celsius to over 1600° Celsius.

The chemical manufacturing subsector is based on the transformation of organic and inorganic raw materials by a chemical process to formulate useful products such as raw materials for synthetic fibers, adhesives, rubber chemicals, and polymer additives. The chemical reactions and process temperatures vary widely within the industry. As of mid-2023, a significant number of the largest chemical manufacturers by market share have made decarbonization commitments of 15–42% by 2030.[158]

Demand for chemical products is expected to increase over time, at approximately 1% per year.[159] Notably, more than 96% of manufactured goods are directly impacted by the chemicals subsector, and as demand for these goods increases over time, the chemical industry is expected to grow as well.[160] However, it should be noted that the buildout of ethylene crackers in the US, including the Shell Petrochemical Complex in Pennsylvania, has created an oversupply of the product and has contributed to lower prices. Industry analysts have suggested that the oversupplied market may never readjust, significantly impacting economics.[161]

Decarbonization Pathway

The complex, multi-product nature of the chemical manufacturing subsector makes it challenging to fully decarbonize. Further, the DOE has identified that even with the ambitious application of existing decarbonization technologies, some residual emissions will remain hard-to-abate such as small dilute sources that are highly distributed across a chemical facility.[162]

The solutions employed to decarbonize the chemical manufacturing subsector include efficiency, fuel switching, and retirement. The IEA identified that catalyst and related process improvements could reduce energy intensity for core chemical industry products by 20-40% by 2050, and therefore an average efficiency improvement of 30% was applied to Pennsylvania's chemical sector linearly beginning in 2025.[163] The remainder of subsector emissions can be reduced through fuel switching. Based on an analysis of the products produced by key facilities in Pennsylvania,[164] Strategen determined that approximately 89% of in-state chemical production processes require high-temperature heat, likely from alternative fuels like hydrogen. Electrification can decarbonize the

155 Based on Strategen analysis.
156 EPA FLIGHT.
157 PA DEP, *Plan Approval Permit #04-00740A*, 2023. https://files.dep.state.pa.us/RegionalResources/SWRO/SWROPortalFiles/Shell/10-10-23/PA-04-00740A%20Oct%202023%20Ext%20Package.pdf.
158 Michel, G. et al., *Decarbonizing Chemicals Part One: Sectorwide Challenges Will Intensify Beyond 2030*, S&P Global, 2023. https://www.spglobal.com/esg/insights/featured/special-editorial/decarbonizing-chemicals-part-one-sectorwide-challenges-will-intensify-beyond-2030.
159 Ibid.
160 Ibid.
161 Sanzillo, T. and Hipple, K., *Shell's Pennsylvania Petrochemical Complex: Financial Risks and a Weak Outlook*, Institute for Energy Economics and Financial Analysis, 2020. https://ieefa.org/articles/ieefa-report-financial-risks-loom-shells-pennsylvania-petrochemicals-complex.
162 DOE, Industrial Decarbonization Roadmap.
163 Ausfelder, F. et al., *Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*, IEA, ICCA, and DECHEMA, 2013. https://iea.blob.core.windows.net/assets/d0f7ff3a-0612-422d-ad7d-a682091cb500/TechnologyRoadmapEnergyandGHGReductionsintheChemicalIndustryviaCatalyticProcesses.pdf
164 The list of facilities was generated from EPA's FLIGHT, part of the GHGRP. While this does not represent all production facilities in the state, it was assumed that this subset provides a representative sample of producers and could be reasonably assumed to provide an average overview of the subsector.

remaining 11% of processes that have low-temperature heating needs. Due to the differences in the commercial availability of hydrogen and electrification, it was assumed that electrification would begin in 2025 and fuel switching to hydrogen would begin in 2030.

The Shell ethylene cracker facility was identified as a candidate for retirement due to its significant contributions to annual emissions in the commonwealth (66% of subsector emissions), issues with plant operations that have led to ongoing shutdowns and violations for excessive pollution,[165] and the significant cost that would be required to decarbonize the plant. A typical ethylene cracker plant costs approximately $5 billion to build and, given the nascency of hydrogen crackers and the need to replace on-site equipment to enable combustion of 100% hydrogen, it is reasonable to assume that conversion to hydrogen may even cost more than this.[166] Fuel switching to hydrogen would likely require full replacement of the burner system. If converted, the Shell plant would require approximately 160,000 tons of clean hydrogen per year to continue its current level of production. With a number of competing uses expected for clean hydrogen in the future, the ongoing challenges experienced with the Shell facility, and uncertainty about future economics, retirement was selected as the most cost effective and environmentally beneficial route. The year 2042 was selected for retirement of the ethylene plant due to the phase-down of state tax breaks for the plant, as well as the typical 20–30-year lifetime of an ethylene cracker.[167]

Through this combination of solutions, Pennsylvania's chemical manufacturing industry would decarbonize 5% by 2030 and 100% by 2050.

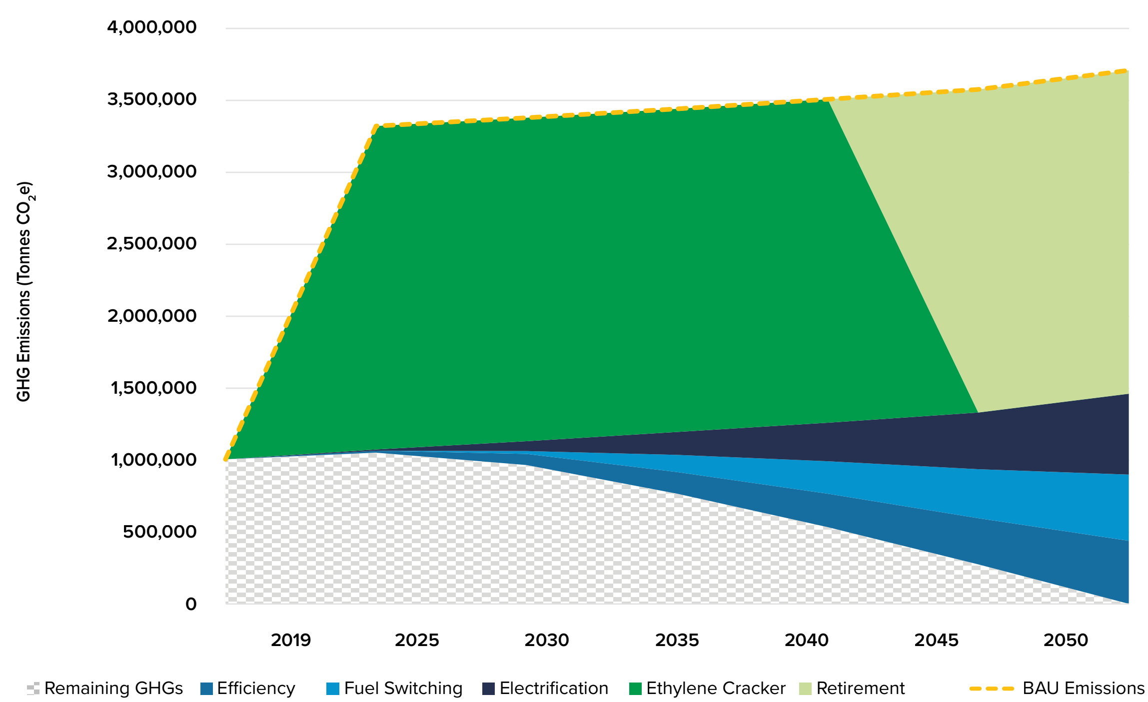


FIGURE 18: Chemical Manufacturing Decarbonization Pathway (2019-2050)

165 Sabados, K., Abou-Sabe, K., and Rappleye, H., "Months After Residents Sound the Alarm, Pennsylvania 'Cracks' down on Shell Plant," NBC News, May 25, 2023. https://www.nbcnews.com/news/us-news/pennsylvania-cracks-down-shell-plastics-cracker-plant-rcna82750; Frazier, R. "Shell's Air Pollution Violations Result in $10 Million Fine for Beaver County Ethane Cracker," State Impact Pennsylvania, May 25, 2023. https://stateimpact.npr.org/pennsylvania/2023/05/25/shells-air-pollution-violations-result-in-10-million-fine-for-beaver-county-ethane-cracker/.

166 The Allegheny Front, "Frequently Asked Questions About Ethane Crackers," Accessed October 18, 2023. http://archive.alleghenyfront.org/story/frequently-asked-questions-about-ethane-crackers.html.

167 Center for Economic Development, *Estimating State and Local Revenue Impacts from Meeting Phase 1 Space Needs for HQ2 If (Pittsburgh Had Won) Part II. Corporate Income Taxes – Appendix*, Carnegie Mellon University Heinz College, 2019. https://www.heinz.cmu.edu/ced/file/hq2-part-2---appendix.pdf; IEA, ICCA and DECHEMA, *Energy and GHG Reductions in the Chemical Industry via Catalytic Processes: Annexes*, 2013. https://iea.blob.core.windows.net/assets/fc71e0ab-aef1-4d06-b9c2-caf293a91c6e/Technology_Roadmap_Catalytic_Processes_Annexes.pdf.

Portfolio Cost

The proposed portfolio will cost approximately $183 million in aggregate, with $68 million in costs for fuel switching and $115 million for electrification. Of note, solutions to decarbonize the Shell ethylene cracker facility, instead of shutting it down, could increase this cost to over $5 billion, more than 50 times the current portfolio cost. Consistent with guidance from DOE, Strategen estimates that energy efficiency improvements will not require significant net expenditures and could potentially result in a positive rate of return.[168] Electrification costs are based on the cost of installing an industrial heat pump, which is estimated to be $23/MWh of heat output in 2021.[169] Expenditures to enable fuel switching are based on the cost of retrofitting to accommodate an industrial-scale hydrogen furnace.[170]

Key Takeaways

+ The chemical manufacturing subsector is responsible for about 3% of industrial emissions in Pennsylvania.
+ Shell's ethylene cracker facility, located in Beaver County, makes up 66% of annual petrochemical sector emissions in Pennsylvania.
+ The following solutions can be utilized to reduce the chemical manufacturing subsector emissions 5% by 2030 and 100% by 2050:
    - It is expected that the chemical manufacturing industry will be 30% more energy efficient by 2050.
    - Approximately 89% of in-state chemical production processes require high-temperature heat, and thus will require fuel switching to decarbonize.
    - Electrification can decarbonize the remaining 11% of processes that have low-temperature heating needs.
    - The Shell ethylene cracker facility was identified as a candidate for retirement due to its significant contributions to annual emissions in the commonwealth, issues with plant operations that have led to ongoing shutdowns and violations for excessive pollution, and the significant cost that would be required to decarbonize the plant. The year 2042 was selected for retirement of the ethylene plant due to the phase-down of state tax breaks for the plant as well as the typical 20 to 30-year lifetime of an ethylene cracker.
    - The proposed portfolio will cost approximately $183 million in aggregate.
+ Decarbonizing the Shell ethylene cracker may increase this cost to over $5 billion.

Refining

The refining subsector is responsible for approximately 4.2% of annual industrial emissions in Pennsylvania. Refineries in Pennsylvania produce a range of products including oils, resins, gasoline, diesel, distillates, and home heating fuel. The refining and chemical manufacturing subsectors are closely interconnected with similar production pathways and opportunities for decarbonization.

At a refinery, crude oil is heated by a furnace and separated by boiling point into usable petroleum products such as gasoline, distillates such as diesel fuel, heating oil, and jet fuel, fuel oil, petrochemical feedstocks, waxes, lubricating oils, and asphalt.

168 Brennan, M. et al., *Pathways to Commercial Liftoff: Decarbonizing Chemicals and Refining*, DOE, 2023. https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Chemicals-Refining_v11.pdf. (Hereafter "DOE, *Pathways to Commercial Liftoff: Decarbonizing Chemicals and Refining*").

169 Rissman, J., Decarbonizing Low-Temperature Industrial Heat.

170 The Economic Times, "Essar to Build UK's First Refinery-Based Hydrogen Furnace in £45 Million Investment," February 9, 2022. https://economictimes.indiatimes.com/news/international/business/essar-to-build-uks-first-refinery-based-hydrogen-furnace-in-45-million-investment/articleshow/89455764.cms?from=mdr/.

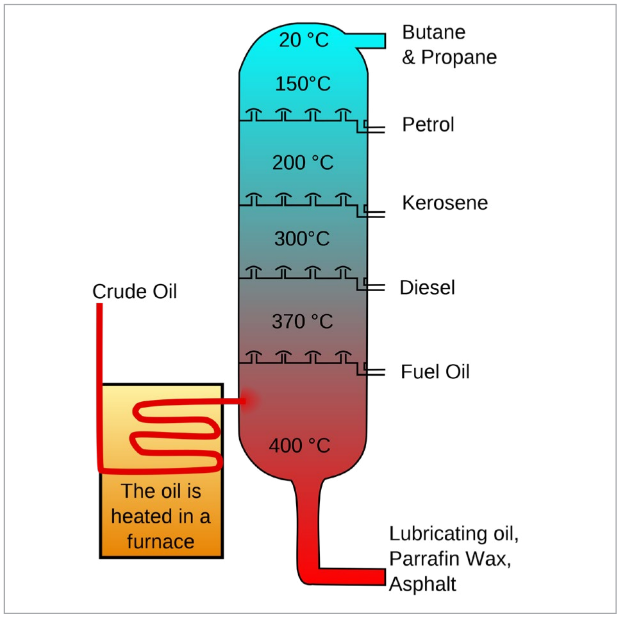


FIGURE 19: Overview of the Refinery Process | *Source: CME Group*

Refinery emissions are categorized into combustion emissions, process emissions, and other emissions. Stationary combustion is the largest source, accounting for 63% of the sector's emissions. Breaking this down further, 9% of combustion emissions are from low-temperature heat needs while the remainder are from high-temperature heat needs.[171] Process emissions make up 31% and come from the fluid catalytic cracker (FCC), which upgrades oil into usable products and the steam methane reformer (SMR), which uses steam and pressure to convert methane into hydrogen. The remaining 6% come from miscellaneous emissions that are often too small for significant direct overhaul. One such source, methane flaring — the process of burning excess methane that isn't recovered or recycled — would shrink as natural gas and refinery fuel gas are phased out by clean electricity generation technologies or hydrogen.[172]

Nearly 90% of fuel use in refining is applied toward process heating, with about 60% of fuel demand supplied by byproduct fuels derived from feedstock in the production process.[173] Most U.S. refineries' process units are highly optimized with integrated process flows, excess heat transferred between process flows and units, and shared steam, electric, cooling water, and wastewater treatment facilities.[174]

Demand for refinery products is expected to decrease over time at approximately 0.34% per year, driven by reduced demand for gasoline and diesel products throughout the economy.[175]

Decarbonization Pathway

Strategen's decarbonization pathway assumes a 38% more energy efficient refining industry by 2050 in alignment with the DOE's assumptions in its Industrial Decarbonization Roadmap and its energy bandwidth study.[176] Efficiency improvements were applied linearly through 2050, beginning in 2025. Combustion emissions can be decarbonized through a combination of electrification for low temperature heat needs and fuel switching for high temperature heat needs. Fuel switching has also been identified as a key solution to produce zero carbon

171 DOE, Pathways to Commercial Liftoff: Decarbonizing Chemicals & Refining.
172 Byrum, Z. and Dellesky, C., "A Low-Carbon Future in the US Depends on Decarbonizing Petroleum Refineries," World Resources Institute, October 21, 2021. https://www.wri.org/insights/technologies-decarbonize-petroleum-refineries.
173 DOE, *U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis: Petroleum Refining Sector*, 2013. https://www.energy.gov/sites/prod/files/2013/11/f4/energy_use_and_loss_and_emissions_petroleum.pdf.
174 Ibid.
175 Smith, R., "The Refinery of the Future: A Dynamic Investment Outlook as Multi-Billion-Dollar Green Capex Spend Looms," S&P Global, November 16, 2021. https://www.spglobal.com/commodityinsights/en/ci/research-analysis/the-refinery-of-the-future.html.
176 DOE, Industrial Decarbonization Roadmap.

process heat and replace the "grey" hydrogen currently used in refineries to remove sulfur and crack heavy refinery streams into finished refined products.[177] It is assumed that electrification can be applied at the beginning of the pathway in 2025 while fuel switching will be commercially available beginning in 2030. The remaining process and other miscellaneous emissions — about 20% of overall subsector emissions after efficiency improvements — will be reduced via CCS. Both fuel switching and CCS were assumed to be deployed linearly beginning in 2030.

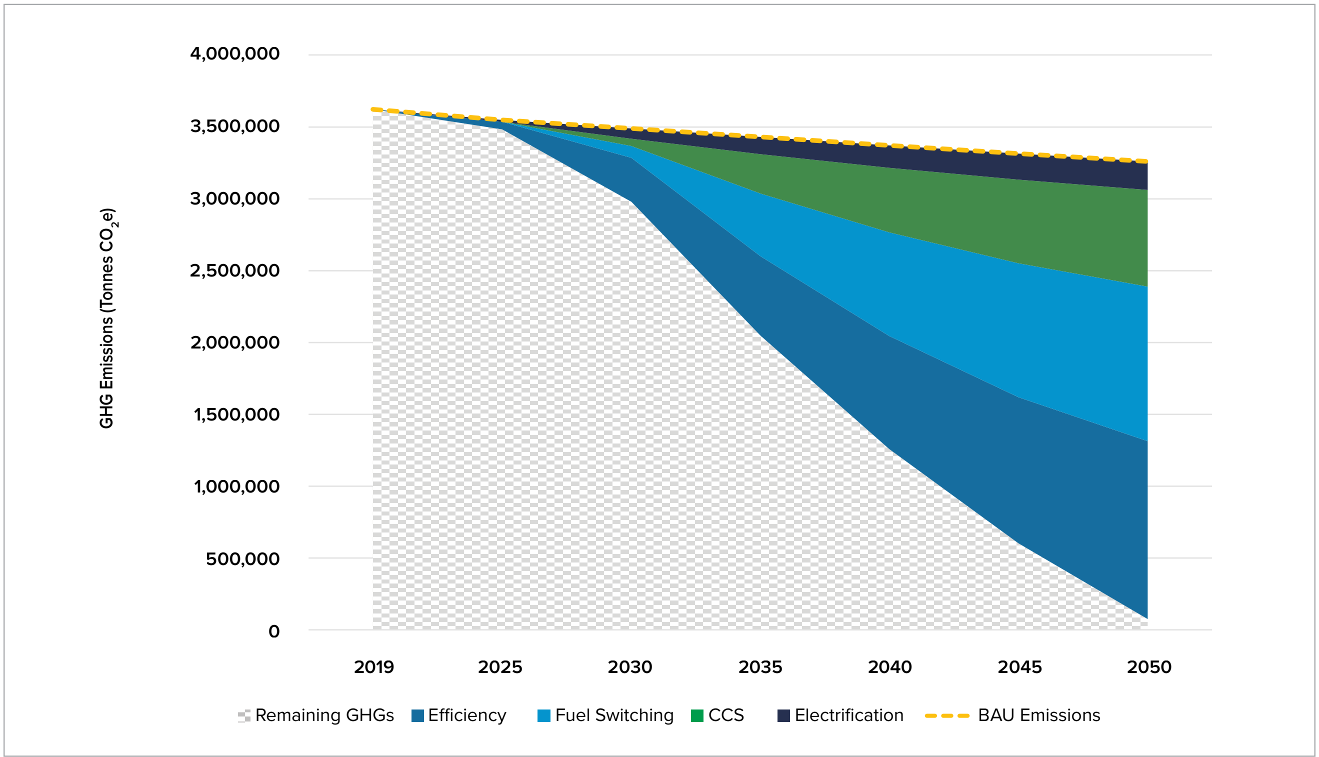


FIGURE 20: Refining Decarbonization Pathway (2019-2050)

Utilizing this combination of solutions Pennsylvania's refining industry can decarbonize 15% by 2030 and 98% by 2050.

In the longer term, as demand for refinery products decreases, there is an opportunity for refinery sites to explore alternative product mixes or on-site uses. For example, refinery sites could be used for storage depots and distribution racks, clean hydrogen production facilities, and energy storage using gas compression or thermal batteries.[178] Refineries could also explore the production of low-carbon transportation fuels such as sustainable aviation fuel.

Pathway Cost

This portfolio will cost $1.3 billion in total, including $163 million for fuel switching, $1.1 billion for CCS, and $43 million for electrification. It is assumed that energy efficiency improvements will not require significant capital expenditures and will ultimately pay for themselves, potentially even resulting in a positive return over time.[179] Fuel switching costs are based on the cost of a hydrogen-based refinery furnace. In the United Kingdom, one of the world's first furnaces capable of running on 100% hydrogen was built for a cost of $48 million. Based on the presence of four refineries in Pennsylvania and the expected total emissions reductions from fuel switching, a $/ton CO_2 reduced cost was developed. Electrification costs are based on the cost of installing industrial heat pumps, assuming $23/MWh of heat output.[180] The cost for CCS was sourced from the Energy Futures Initiative.[181]

177 Grey hydrogen is created from natural gas, or methane, using steam methane reforming but without capturing the greenhouse gases made in the process.
178 Veysey, D., Peltier, M. and Fallurin, J., "Five Ways US Oil Refineries Can Reduce Emissions Today," RMI, June 5, 2023. https://rmi.org/how-to-slash-refinery-emissions-quickly-washington-state/.
179 DOE, Pathways to Commercial Liftoff: Decarbonizing Chemicals and Refining.
180 Rissman, J., Decarbonizing Low-Temperature Industrial Heat.
181 EFI CCS 2023.

Key Takeaways

+ The refining subsector is responsible for 4.2% of industrial emissions in Pennsylvania.
+ Refinery emissions are categorized into combustion emissions, process emissions, and other emissions. Stationary combustion is the largest source, accounting for 63% of the sector's emissions. Process emissions make up 31% and come from the fluid catalytic cracker (FCC), which upgrades oil into usable products and the steam methane reformer (SMR), which uses steam and pressure to convert methane into hydrogen. The remaining 6% come from miscellaneous sources.
+ The following solutions can be utilized to reduce mineral subsector emissions 15% by 2030 and 98% by 2050:
  – Strategen's decarbonization pathway assumes a 38% more energy efficient refining industry by 2050 in alignment with the DOE's assumptions in its Industrial Decarbonization Roadmap and its energy bandwidth study.
  – Electrification can provide a solution to decarbonize low temperature heat needs.
  – Fuel switching has been identified as a key solution to produce high temperature zero carbon process heat and replace the grey hydrogen currently used in refineries.
  – The remaining process and other miscellaneous emissions — about 20% of overall subsector emissions after efficiency improvements — will be reduced via CCS.
+ The implementation of this portfolio of solutions will cost $1.3 billion in aggregate.

Glass

Pennsylvania is home to seven major glass manufacturing facilities, including two flat glass manufacturing facilities, three container glass facilities, and two smaller specialty glass facilities. Together, the Pennsylvania glass industry emits 816,651 metric tons of CO_2e annually, contributing 1% of the commonwealth's industrial emissions.

Glass is made primarily from silica sand with lime, soda, cullet (recycled glass), and other ingredients added. The mixture is then melted together at a high temperature. Different types of glass can have different production methods, but the basic steps of production include the following:

Sand, soda ash, potash, and cullet are combined with stabilizers including magnesium oxide, aluminum oxide, and lime. These materials are ground together into a uniform mixture, typically called "batch." This process is almost entirely performed using electricity.

The resulting batch is melted in a furnace at high temperatures (1,200–1,600 C) achieved by either fossil fuel combustion, electricity, or a combination of both. In the furnace, the materials are also fined, which involves the removal of bubbles and homogenization. Most glass furnaces in the United States are fueled by natural gas, and some use electric boosters, as glass becomes a conductor at high temperatures. When using boosters, electricity may provide up to 20% of the total furnace energy input. Electric boost usage is less common in furnaces producing flat glass.

Glass is transferred into a forehearth where it is conditioned to a desired temperature range (600-1,200 C), then delivered to shaping and forming equipment. Various lower temperature processes are applied to treat the glass, which may include annealing, toughening, and coating.

Due to the high temperatures necessary for melting the raw materials, glass manufacturing is a highly energy intensive process that generates significant emissions from fossil fuel combustion.[182] Glass manufacturing also

182 Zier, M. et al., *A Review of Decarbonization Options for the Glass Industry, Energy and Conversion Management*, June 2021. https://doi.org/10.1016/j.ecmx.2021.100083.

generates process-related emissions from the melting and decomposition of carbonate raw materials such as limestone, dolomite, and soda ash. 84% of emissions come from combustion of fossil fuels, while 16% are process emissions.[183] The glass industry is expected to increase 21% by 2050 in alignment with EIA projections.[184]

Decarbonization Pathway

Decarbonization pathways for the glass industry will involve a combination of measures to reduce energy-related emissions, including fuel switching, electrification, and energy efficiency, as well as measures to avoid process emissions, including material efficiency and CCS.

Waste heat can be recovered and reused to reduce overall energy demand and energy-related emissions. This heat can be reused for preheating of combustion gases, raw materials and cullet, onsite building heating and cooling, electricity generation, or offsite heating needs through district heating systems. Oxyfuel furnaces using oxygen instead of combustion air require less energy input, mitigating energy losses 25-35% relative to a conventional furnace as well as reducing emissions of NO_x.[185] In Strategen's pathway energy efficiency is deployed immediately and assumed to reduce 20% of 2050 combustion-related emissions by 2040.

Increased recycling of glass can significantly reduce CO_2 emissions from this subsector. Mixing recycled glass (cullet) with raw materials, or using cullet entirely, avoids both energy-related and process CO_2 emissions. Energy-related emissions are avoided due to cullet's lower melting temperature relative to the raw materials used in glassmaking, requiring less energy to produce heat. Every 20% addition of cullet saves about 2.5% of furnace energy.[186] Process-related emissions are avoided because the carbonate raw materials that cullet replaces (limestone, dolomite, and soda ash) directly release CO_2 through chemical reactions in the furnace. The rate of glass recycling in the U.S. is only 30% compared to 60% in Europe, so there is potentially significant room for improvement. [187] O-I Glass, the biggest container glass producer in Pennsylvania, has established goals of 50% recycled content by 2030.[188] In Strategen's pathway, material efficiency reduces 50% of process-related emissions and 5% of combustion-related emissions due to lower heating needs.

Clean hydrogen can be substituted for fossil fuels to provide the high temperatures needed for the melting of raw materials and the forming stage. In Europe, there are a number of demonstration projects underway testing the use of hydrogen in the glass industry with encouraging results. Earlier this year Saint-Goban successfully achieved the first flat grass production using more than 30% hydrogen.[189] In Strategen's pathway, fuel switching reduces 15% of combustion related emissions by 2050.

While electricity-based technologies typically are not used to reach high temperatures such as those required for melting, unique solutions have been developed and commercialized for glass melting. Electrodes are submerged in the melt and an electric current is run through it, with a gas burner being used for the initial startup. Some research indicates that electric melting is the most energy-efficient method for furnaces.[190] Furnaces used in glass manufacturing must be rebuilt every 10-15 years, providing significant opportunities for upgrades, retrofits, or replacements.[191] Generally, all-electric melting is only used for smaller furnaces, but in theory there is no technological limitation that would prevent its application in furnaces of higher size.[192] These larger furnaces may take time,

183 DOE, Industrial Decarbonization Roadmap.
184 EIA, "Annual Energy Outlook 2023, Table 28: Glass Industry Energy Consumption," 2023. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=39-AEO2023&cases=ref2023&sourcekey=0.
185 Furszyfer Del Rio, D. et al., *Decarbonizing the Glass Industry: A Critical and Systematic Review of Developments, Sociotechnical Systems and Policy Options*, Renewable and Sustainable Energy Reviews, March 2022. https://doi.org/10.1016/j.rser.2021.111885. (Hereafter "Furszyfer Del Rio, D. et al., Decarbonizing the Glass Industry").
186 British Glass, *Glass Sector Net Zero Strategy 2050*, 2021. https://www.britglass.org.uk/sites/default/files/British%20Glass%20-%20Net%20Zero%20Strategy.pdf. (Hereafter "British Glass, Net Zero Strategy").
187 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.
188 O-I, *2023 Sustainability Report Update*, 2023. https://www.o-i.com/wp-content/uploads/2023/06/2023-Sustainability-Report-Update-English.pdf.
189 Saint-Goban, "Saint-Goban Achieves the First Flat Glass Production Using More Than 30% Hydrogen," March 30, 2023. https://www.saint-gobain.com/en/news/saint-gobain-achieves-first-flat-glass-production-using-more-30-hydrogen.
190 Furszyfer Del Rio, D. et al., Decarbonizing the Glass Industry.
191 British Glass, Net Zero Strategy.
192 Ibid.

however, to reach commercialization. Oxyfuel hybrid furnaces running on 80% electricity could allow for partial electrification in the shorter term in the container glass sector. Electrification provides significant sector reductions in this pathway, reducing 60% of annual combustion-related emissions by 2050.

While combustion emissions can be eliminated by fuel switching and electrification, the process emissions are more challenging and may require CCS to capture residual emissions and eventually reach net zero emissions in this sector. There may also be opportunities to combine the technology with biofuel to yield negative CO_2 emissions, but Strategen's pathway does not assess this possibility. In this pathway, CCS is predicted to reduce 50% of process-related emissions by 2050.

Using this combination of solutions, CO_2e emissions from Pennsylvania's glass industry can be reduced 13% by 2030 and 99% by 2050.

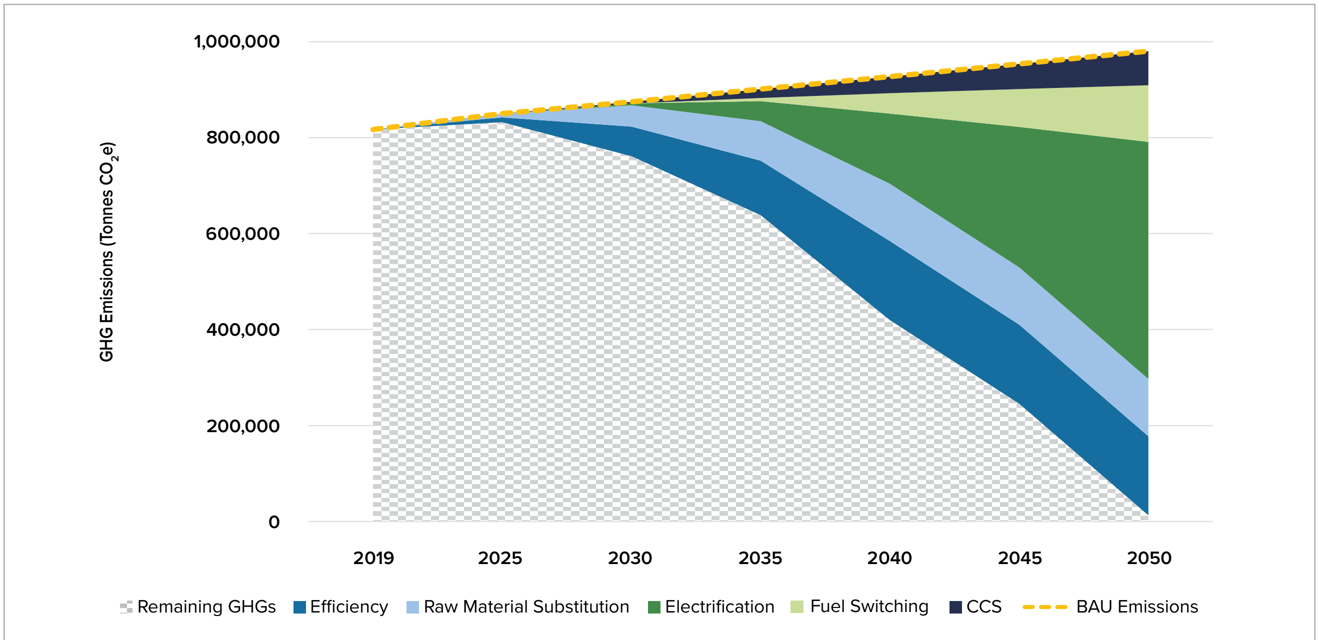


FIGURE 21: Glass Manufacturing Decarbonization Pathway (2019-2050)

Portfolio Cost

The implementation of this portfolio of solutions will cost $646 million. Costs for efficiency solutions and fuel switching are $145 million and $270 million, respectively, and are based on DOE-reported abatement costs for oxy-fuel combustion and hydrogen melting furnaces.[193] CCS costs, which total $118 million for this subsector, are based on estimates from the Energy Futures Initiative.[194] Electrification costs of $111 million are based on glass melting furnace capital costs developed by WSP.[195]

Key Takeaways

+ The glass subsector is responsible for 1% of annual industrial emissions in Pennsylvania.
+ 84% of emissions are from the combustion of fuels for heat and 16% are process emissions from chemical reactions involved in production.

193 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.
194 EFI CCS 2023.
195 WSP, DNV GL, *Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050: Glass Appendices*, UK Department of Energy and Climate Change, 2015. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/415958/Glass_Appendices.pdf.

+ The following solutions can be utilized to reduce glass subsector emissions 13% by 2030 and 99% by 2050:
  - Energy efficiency measures can eliminate approximately 20% of combustion emissions.
  - Increasing the usage of recycled glass can reduce combustion emissions by 5% due to lower heating needs and process emissions by 50% due to fewer carbonate materials in the batch.
  - Electrification, mainly of melting furnaces, can reduce combustion emissions by 60%
  - Fuel switching can reduce combustion emissions by 15%.
  - The decarbonization of process emissions will require CCS, reducing emissions in this category by 50%.
+ The implementation of this portfolio of solutions will cost $646 million in aggregate.

Pulp and Paper

Pulp and paper emissions in Pennsylvania from 2019 are estimated at approximately 2.7 $MMTCO_2e$, or 3.1% of total industrial emissions in the commonwealth. Pennsylvania facilities produce a wide range of paper products, including toilet paper, paper towels, specialty papers, paperboard, and uncoated papers.

The EPA divides the pulp and paper subsector into one category for chemical pulp and paper manufacturing and a second for other paper producers. Chemical pulp and paper includes facilities that use chemical pulping processes to manufacture pulp and integrated paper mills that produce pulp for use in onsite paper making, while other paper producers consist of facilities that use non-chemical pulping processes or non-integrated facilities that purchase pulp to produce paper products. The other paper producers category also includes facilities that produce secondary fiber from recycled paper, convert paper into paperboard products, operate coating and laminating processes, or produce alternative paper products such as newspapers, books, labels, and stationery.[196]

In Pennsylvania, this industry includes both chemical pulp and paper mills and other paper producers. Approximately 60% to 70% of the commonwealth's large pulp and paper facility emissions come from other paper producers. Facilities reported in EPA's data also reveal an uneven distribution of emissions, with over 50% of 2019 emissions coming from the two largest facilities, and over 35% coming from a single producer.

The pulping process includes separating and removing lignin to obtain fiber or cellulose from wood raw materials. There are three general classes of pulping processes: mechanical, chemical, and semi-mechanical. Regardless of class, all pulp manufacturing begins with raw wood materials. The bark is removed and converted into chips. Once the pulp has been produced, it is bleached before being sent on to paper production processes.[197]

In mechanical pulping processes, the chips are milled to release fibers and then filtered to separate the cellulose. Pulp from mechanical processes can still have a higher lignin content than pulp from chemical processes, but the yield of pulp from mechanical processes is 90% to 98%. Mechanical processes require considerable amounts of electric power but have no direct CO_2 emissions.[198]

In chemical pulping, chips are put through a cooking process, which occurs in a large, pressurized digester. The purpose of the cooking process is to dissolve the lignin component in wood, using chemicals and heat. The chemical pulping process typically yields 40% to 50% of the dry weight of the original wood input.[199] Chemical pulping processes require large amounts of steam, but they also produce a by-product of black liquor, a chemical that can be combusted to generate steam and electricity.[200] This can help offset the energy required for the process.

196 EPA, *2011-2021 Greenhouse Gas Reporting Program Sector Profile: Pulp and Paper*, 2023. https://www.epa.gov/system/files/documents/2023-05/Pulp_and_Paper_Profile_RY2021_05-04-2023%20508.pdf.
197 Rullifank, K. et al., *Pulp and Paper industry: An Overview on Pulping Technologies, Factors, and Challenges*, IOP Conference Series: Materials Science and Engineering, 2020. https://doi.org/10.1088/1757-899X/845/1/012005. (Hereafter "Pulping Technologies, Factors, and Challenges").
198 Pulping Technologies, Factors, and Challenges.
199 Briggs, D., "Chapter 8: Pulp and Paper," in *Forest Products Measurements and Conversion Factors*, 1994. http://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_ch08/chapter08_combined.pdf.
200 Pulping Technologies, Factors, and Challenges.

Semi-mechanical processes use chemical processes or heat to remove or weaken cellulose lignin bonds and improve the fiber separation achieved by mechanical processes. This improves yield to 65% to 85%, but since the process is more complex, it often requires larger production costs.[201]

Paper production processes vary by end product. First, pulp is combined with dyes, resins, filler material, and water to achieve the desired properties. Next, some of the water is removed through gravitational forces and vacuums and the paper then passes through a press, which mechanically removes additional water. Following these steps, all remaining water is removed thermally, in drying processes, which is generally the most energy-intensive stage of production.

The pulp and paper sector generates both biogenic and non-biogenic CO_2 emissions. Biogenic CO_2 comes from the combustion of pulping liquors (i.e., biomass) in chemical recovery combustion units and from the combustion of wood fuels in combustion units. Non-biogenic CO_2 comes from fossil fuel combustion in chemical recovery systems, lime kilns, and other fuel combustion sources; and from the addition of carbonaceous makeup chemicals in chemical recovery systems.[202] This analysis treats biogenic CO_2 emissions as out of scope, in alignment with the estimates developed by DEP's GHG Inventory.[203]

Based on projections from the EIA AEO Reference Case for 2023, production is assumed to increase by approximately 9% over the study period.[204]

Decarbonization Pathway

Pulp and paper sector emissions come from two primary sources: heat generation (68%) and electricity (32%).[205] The heat generation needs can be further broken down into low (79.4%), medium (10.3%), and high (10.3%) temperature requirements.[206] As a large portion of the heat required for paper production is low-temperature heat (79.4% of heat needs), industrial heat pumps can be used to replace steam and power that is currently generated through fossil combustion. Electrification is assumed to be deployed linearly beginning in 2025 with decarbonization potential consistent with the projected decarbonization of the power grid. Additionally, existing electric uses in the pulp and paper sector are expected to decarbonize over time, consistent with power sector decarbonization.

Fuel switching will be needed to decarbonize medium and high temperature heat needs. Alternative fuels that have been considered to decarbonize the pulp and paper industry include both biomass and clean hydrogen in burners and boilers. Currently, the industry gets over 60% of its fuel needs from biomass,[207] so it is expected that biomass will continue to play a significant role in decarbonization. As biomass is already used and is commercially available today, it is expected that fuel switching will begin in 2025 and be deployed linearly over time.

Energy efficiency measures are also a key decarbonization lever for the pulp and paper industry. These measures vary by facility, but DOE estimates that energy efficiency accounts for 15% of sector abatement potential.[208] An average energy efficiency improvement of 15% was applied to Pennsylvania's pulp and paper sector linearly beginning in 2025. This will result in 14.5% decarbonization by 2030 and 100% by 2050.

202 EPA, *2010-2011-2012 GHGRP Industrial Profiles: Pulp and Paper Sector*, 2016. https://epa.gov/sites/production/files/2016-11/documents/pulp_and_paper_2012_ip_110416.pdf.
203 Pennsylvania GHG Inventory.
204 EIA, "Annual Energy Outlook 2023, Table 26: Paper Industry Energy Consumption," 2023. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=37-AEO2023&cases=ref2023&sourcekey=0.
205 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.
206 Ibid.
207 Ibid.
208 Ibid.

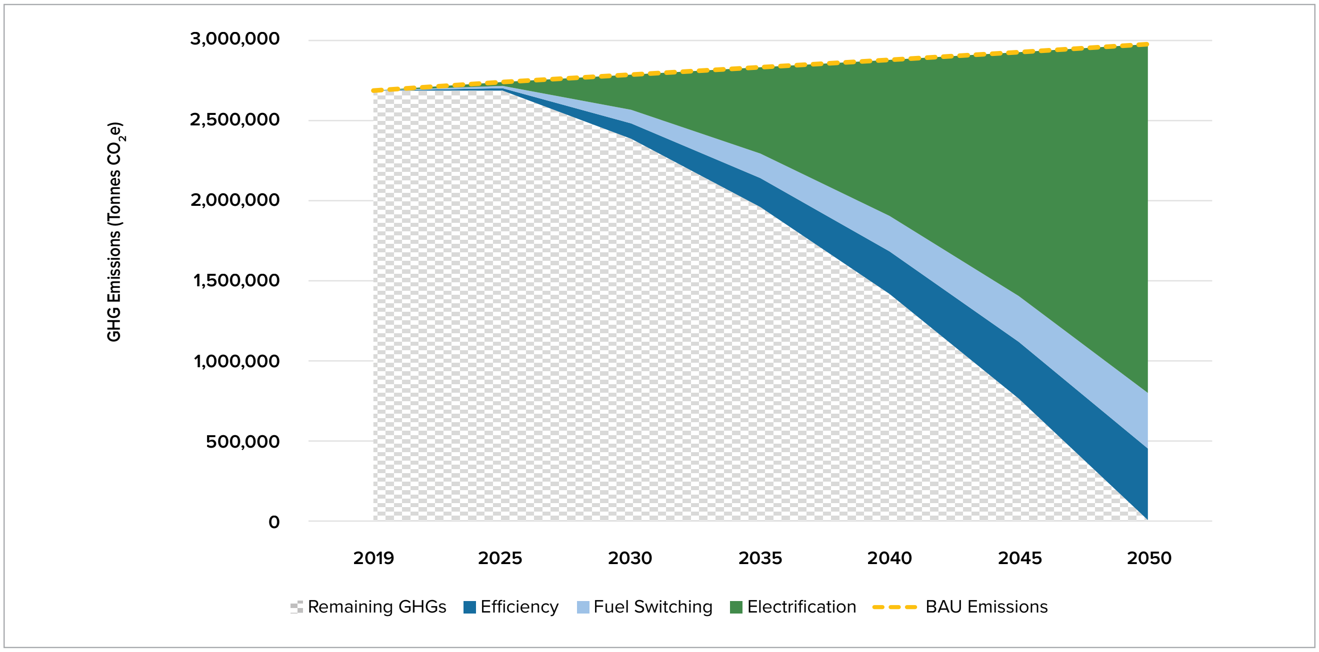


FIGURE 22: Pulp and Paper Decarbonization Pathway (2019-2050)

Portfolio Cost

The estimated cumulative cost to decarbonize this subsector is $738 million, including $297 million for fuel switching and $441 million for electrification. Energy efficiency improvements are not anticipated to result in significant net expenditures and could potentially lead to a positive return over time.[209] Electrification costs are based on the cost of installing industrial heat pumps. This cost is estimated to be $23/MWh of heat output.[210] Fuel switching costs are based on the average alternative fuels abatement cost for the pulp and paper sector, as reported in DOE's *Pathways to Commercial Liftoff* report focused on the industrial sector.[211]

Key Takeaways

+ The pulp and paper subsector is responsible for 3.1% of industrial emissions in Pennsylvania.
+ Pulp and paper sector emissions come from two primary sources: heat generation (68%) and electricity (32%). The heat generation needs can be further broken down into low (79.4%), medium (10.3%), and high (10.3%) temperature requirements.
+ The following solutions can be utilized to reduce pulp and paper subsector emissions 14.5% by 2030 and 100% by 2050:
  – Electrification can be used to decarbonize low-temperature heating needs. Additionally, existing electric uses in the pulp and paper sector are expected to decarbonize over time, consistent with power sector decarbonization.
  – Fuel switching will be needed to decarbonize medium and high temperature heat needs.
  – It is estimated that energy efficiency accounts for 15% of sector abatement potential.
+ The implementation of this portfolio of solutions will cost $738 million in aggregate.

209 DOE, Pathways to Commercial Liftoff: Chemicals and Refining.
210 Rissman, J., Decarbonizing Low-Temperature Industrial Heat.
211 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.

Food Processing and Miscellaneous Manufacturing

This category encompasses emissions from a suite of industrial manufacturing facilities, with the most common being food processing and wallboard manufacturing. These facilities manufacture a wide variety of products but make up a small portion of Pennsylvania's industrial emissions (1.8%) and share common solutions for decarbonization.

Nearly 90% of large food and beverage manufacturers have decarbonization commitments spanning all facilities.[212] The first net-zero gypsum wallboard facility began production earlier this year in Norway, with the first net-zero facility in North America scheduled to come online in late 2024.[213]

While specific manufacturing processes differ across facilities in this category, the majority use low-temperature heat and steam fueled by natural gas combustion. Given that it represents the greatest number of facilities in this category, food processing is used as a proxy in Strategen's analysis. The many low-temperature processes involved in these manufacturing facilities include drying, dehydration, canning, blanching, and melting.

Demand, and associated emissions, from this sector are assumed to increase 25% by 2050, in line with projections from the DOE.[214]

Decarbonization Pathway

The large majority of direct emissions from this category come from the combustion of fossil fuels to achieve low-temperature heat.

Efficiency solutions are a near-term and cost-effective decarbonization solution for this subsector. Mature and proven technologies such as waste heat recovery, more efficient oven burners, and better energy management solutions have significant potential to reduce emissions. The pathway assumes a 27% more efficient industry by 2050, in alignment with DOE's energy bandwidth study.[215]

There are significant opportunities for electrification in this subsector, relative to other industries, given the lower temperature heat requirements. Certain electrification technologies like electric boilers are currently deployable, and many types of industrial heat pumps are also in the demonstration phase. Renewable Thermal Collective projects that electrification will be able to provide more that 85% of process heat in the sector.[216] In Strategen's pathway, electrification reduces 90% of emissions by 2050 after efficiency improvements.

Certain higher temperature heat processes may still exist in this category, for which combustion of hydrogen can potentially serve as a solution, reducing emissions 10% by 2050 after efficiency.

Through this combination of solutions, Pennsylvania's CO_2e emissions from this category are reduced 12% by 2030 and 100% by 2050.

212 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.

213 Global Gypsum, "Saint-Gobain Starts Net Zero Gypsum Wallboard Production in Norway," April 14, 2023. https://www.globalgypsum.com/news/item/1959-saint-gobain-starts-net-zero-gypsum-wallboard-production-in-norway ; Saint-Gobain, "Saint-Gobain to Create the First Net-Zero Carbon Plasterboard Plant in North America," June 9, 2022. https://www.saint-gobain.com/sites/saint-gobain.com/files/media/document/20220609_Montreal_VA.pdf.

214 DOE, Industrial Decarbonization Roadmap.

215 Cresko, J. et al., *Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Food and Beverage Manufacturing*, DOE, 2017. https://www.energy.gov/sites/default/files/2019/05/f62/Food_and_beverage_bandwidth_study_2017.pdf.

216 Yuan, C. and Riley, D., *Playbook for Decarbonizing Process Heat in the Food and Beverage Sector*, Renewable Thermal Collective, 2023. https://www.renewablethermal.org/wp-content/uploads/2018/06/WWF-RTC-Playbook-for-Decarbonizing-Process-Heat_FoodBev_Final.pdf.

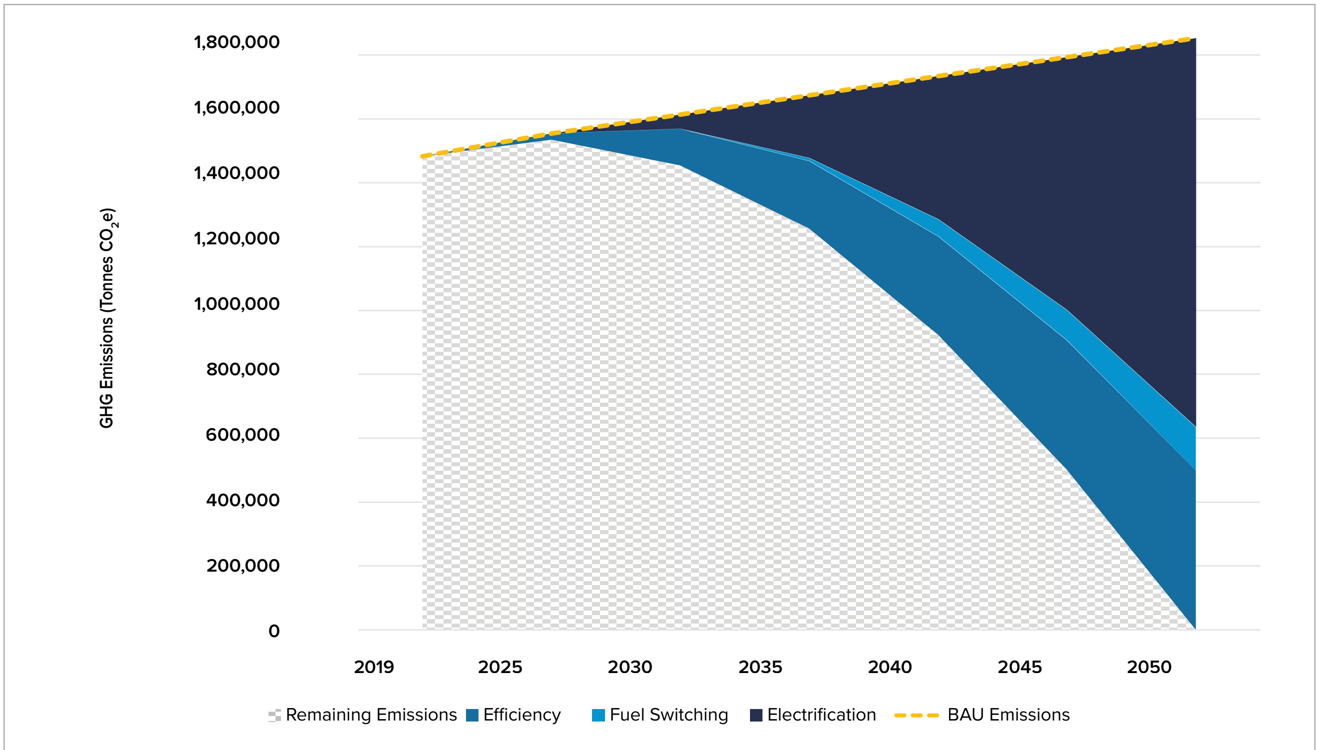


FIGURE 23: Food Processing and Miscellaneous Manufacturing Decarbonization Pathway (2019-2050)

Portfolio Cost

The implementation of this pathway is estimated to cost $640 million in aggregate. As with other subsectors, it is assumed that energy efficiency improvements will not require significant capital expenditures and may even result in a positive return on investments.[217] Fuel switching costs of $2 million are based on the estimated cost of conversion from natural gas combustion to hydrogen.[218] Electrification costs of $638 million are based on the abatement cost for electrifying industrial heat in the food sector provided by DOE.[219]

Key Takeaways:

+ This subsector is responsible for 1.8% of industrial emissions in Pennsylvania.
+ The most common facilities in this subsector are food processing and wallboard manufacturing.
+ This subsector consists almost entirely of low-temperature heat processes.
+ The following solutions can be utilized to reduce subsector emissions 11% by 2030 and 100% by 2050:
  - It is expected that the industry will be 27% more energy efficient by 2050.
  - Since nearly all emissions come from low-temperature process heat electrification is a major decarbonization lever, accounting for 90% of further emissions reductions by 2050.
  - Fuel switching is assumed for the small amount of high-temperature process heat, accounting for 10% of further emission reductions by 2050.
+ The proposed portfolio will cost approximately $640 million in aggregate.

Other Low Heat Subsectors

As previously discussed, Strategen's analysis incorporated data from both the GHG Inventory and the EPA GHGRP in developing a 2019 baseline for industrial sector emissions in Pennsylvania. Given that the GHG Inventory only provides on industrial sector emissions from fossil fuel combustion at an aggregate level, data from the GHGRP

217 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.
218 Durusut, E. et al., Conversion of Industrial Heating Equipment.
219 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.

were employed to allocate combustion emissions to each industrial subsector examined in the analysis. Although these two datasets are complementary, they are constructed using different methodologies, with the GHG Inventory data assembled through a top-down approach based on estimates of fuel consumption, and the GHGRP data collected from the bottom-up based on reporting at the facility level. As a result, when allocating data on industrial sector fossil fuel combustion from the GHG Inventory to each of the reporting industrial subsectors, there are excess emissions that cannot be further attributed to the other subsectors under study. These emissions are therefore assigned to the Other Low Heat Subsectors category.

Strategen assumes that the majority of emissions in this category are attributable to stationary fossil fuel combustion, requiring lower temperature heating. As mentioned in the Pennsylvania Greenhouse Gas Inventory Report, industrial sector combustion emissions include those resulting from burning fuel to heat and cool industrial buildings.[220] Additionally, in its Inventory of U.S. Greenhouse Gas Emissions and Sinks, EPA notes that although the majority of fuel consumption assigned to the industrial sector can be attributed to industrial customers, this category can also include emissions from the combustion of fuels delivered to large customers in other sectors, such as agriculture, construction, and large commercial facilities.[221]

Decarbonization Pathway

Based on the assumption that the emissions in this category result from combustion to achieve low-temperature heat, Strategen employs the same set of solutions applied for similar heating needs, primarily energy efficiency measures and electrification. In this subsector, 75% of emissions are addressed through the electrification, through the retrofit of fossil fuel combustion equipment with electric heat pumps and boilers. Reductions are applied based on the difference between existing emissions intensity and the emissions intensity of the electric grid, which is assumed to fully decarbonize by 2050. The remaining portion of emissions in this category can be partially reduced through an energy efficiency path, where efficiency improvements of 25% are assumed by 2050.

In contrast to other industrial subsectors, in which more detail is available on specific processes and potential levels of solutions that can be feasibly applied, the decarbonization methodology for this pathway is driven instead by decreases necessary to reach industrial sector-wide greenhouse gas reductions of at least 80% by 2050.

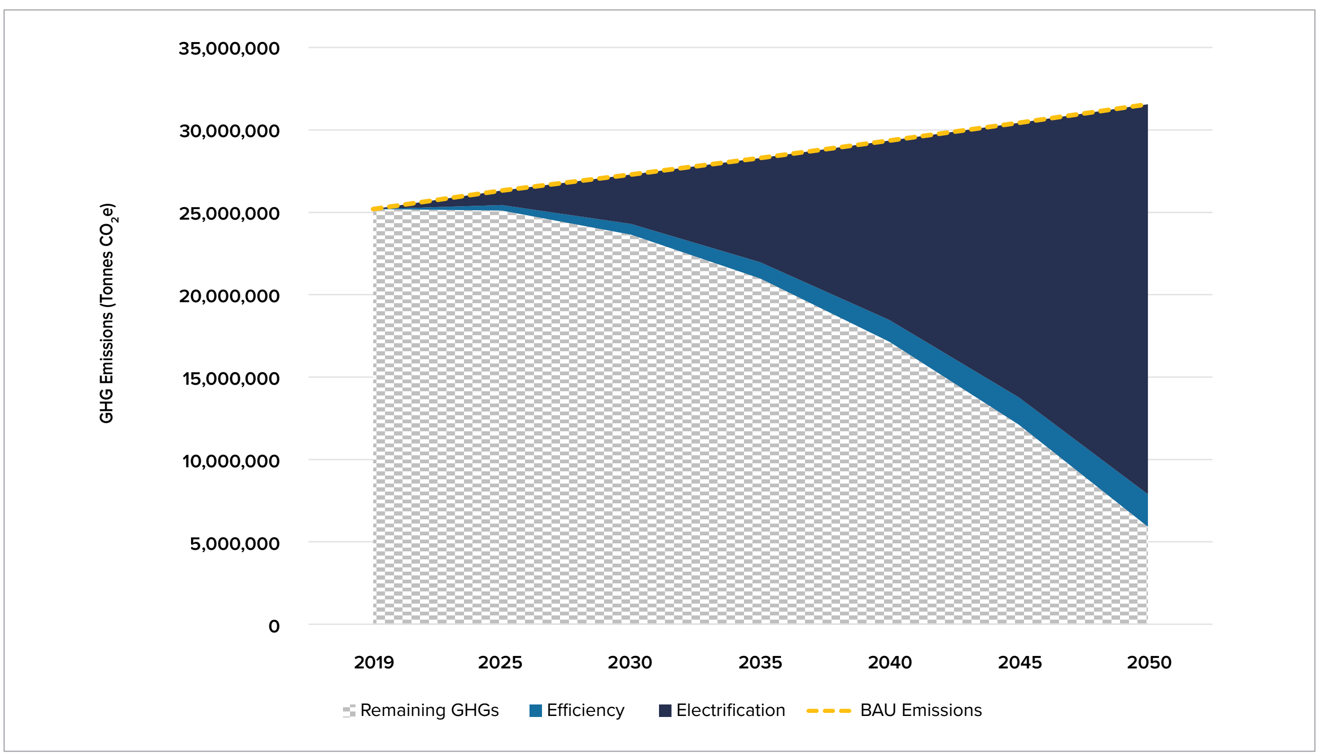


FIGURE 24: Other Low Heat Subsectors Decarbonization Pathway (2019-2050)

220 Pennsylvania GHG Inventory.
221 EPA GHG Inventory.

Portfolio Cost

Based on the assumed penetration of solutions described above, Strategen estimates implementation costs for this category to reach $14.6 billion, driven by electrification expenditures calculated using DOE's abatement cost for electrifying low-temperature industrial heat.[222] With limited information available about the specifics of this category, Strategen also assumed that energy efficiency improvements would pay themselves over time.

Key Takeaways:

+ This subsector is responsible for 29.2% of industrial emissions in Pennsylvania.
+ Emissions from this subsector consist of fossil fuel combustion for low-temperature process heat in a wide range of activities such as mining, agriculture, construction, large commercial and other manufacturing
+ The following solutions can be utilized to reduce subsector emissions 13% by 2030 and 76% by 2050:
    - 75% of emissions are addressed through the electrification, through the retrofit of fossil fuel combustion equipment with electric heat pumps and boilers.
    - The remaining portion of emissions in this category can be partially reduced through an energy efficiency path, where efficiency improvements of 25% are assumed by 2050.
+ The proposed portfolio will cost approximately $14.6 billion in aggregate.

Fluorinated GHGs

Fluorinated gases include a range of artificial gases used in a variety of household, commercial, and industrial applications and processes. Hydrofluorocarbons (HFC) and perfluorocarbons (PFC) are widely adopted as substitutes for ozone-depleting substances (ODS), while gases like sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3), among others, are used in the manufacturing of semiconductors. These gases are released in relatively small quantities during their production, in the manufacturing of products, and during the use and disposal of such products.[223]

While fluorinated gases do not deplete the ozone layer, they have a significant impact on global warming. HFCs, for example, have a 100-year global warming potential (GWP) of 14,800. These potent GHG emissions could grow rapidly following the demand for their related products, and therefore steps have already been taken globally and domestically to phase down the production and use of fluorinated gases. The Kigali Amendment to the Montreal Protocol, which came into effect in 2019, aims to phase down the production and consumption of HFCs globally. This agreement encourages the use of more environmentally friendly alternatives, such as hydrofluoroolefins (HFOs) and natural refrigerants. In the United States, the American Innovation and Manufacturing (AIM) Act was enacted in 2020 authorizing the EPA to address HFCs by providing new authorities to phase down the production and consumption of listed HFCs, manage these HFCs and their substitutes, and facilitate the transition to next-generation technologies through sector-based restrictions. More recently, the IRA provided $38.5 million to carry out implementation of and compliance with the AIM Act. Of this funding, $15 million is for competitive grants for reclaim and innovative destruction technologies.

The AIM Act directs EPA to phase down the production and consumption of HFCs by 85% by 2036 through an allowance allocation and trading program. The cap started with a 90% emission allowance (based on 2020 levels) for the 2022-2023 period, and will be reduced until it reaches 15% in 2036, consistent with the phasedown schedule in the Kigali Amendment.[224] This transition away from HFCs is expected to have large benefits for

222 DOE, Pathways to Commercial Liftoff: Industrial Decarbonization.

223 Fluorinated gases also appear in final products such as air-conditioning, refrigeration, fire protection, aerosols and solvents, insulation for electronics and electric power systems.

224 A global phasedown of HFCs consistent with the Kigali Amendment is expected to avoid up to 0.5°C of global warming by 2100. Prior to the implementation of the Kigali Amendment, HFC usage was growing at between 10-15% per year. Without action under the Kigali Amendment, emissions of these gases would be on a trajectory to double every five to seven years.

American consumers; the EPA estimates that the monetized net present cumulative benefits of all provisions of the HFC phasedown from 2022 through 2050 are estimated to be $269.9 billion.[225]

For this decarbonization pathway, Strategen assumed that the HFC phasedown schedule will be accomplished and that emissions from ODS substitutes will be reduced by 85% by 2036 as part of the base case scenario. It also assumes that the emissions of other fully fluorinated gases, like SF6 and NF3, will remain stable at very low levels, considering that their use is already being decreased by past regulations. These assumptions correspond to a decrease from 5.1 $MMTCO_2e$ emissions from the sector in 2019 to 0.9 $MMTCO_2e$ by 2036 and carried thereafter.

Summary of Pathways

This roadmap illustrates a technologically feasible pathway to reduce industrial emissions in Pennsylvania by 21% from 2019 levels, or 18.2 MMT of CO_2e per year, by 2030 and 84%, or 72.6 MMT of CO_2e annually, by 2050. Emissions from all industrial subsectors, including fossil fuel extraction and delivery, iron and steel, minerals (e.g., cement, lime), chemicals, and refining, were assessed. Notably, the significant baseline emissions from fossil fuel extraction and delivery and low heat subsectors means that these subsectors significantly contribute to remaining industrial emissions at the end of the period. The collective reductions for each subsector are presented in *Figure 25*.

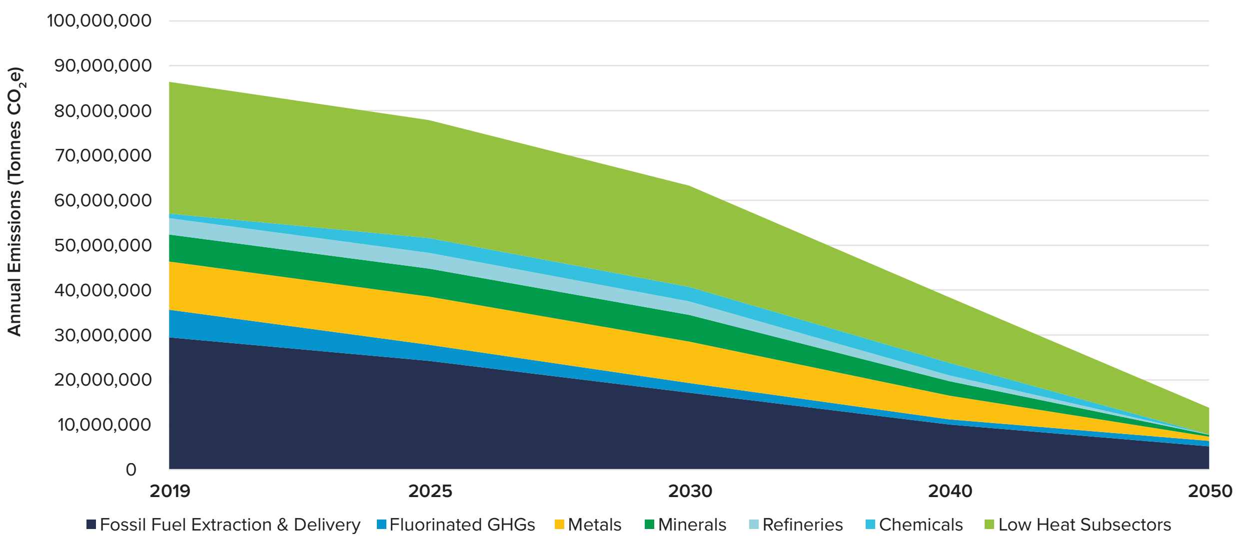


FIGURE 25: Pennsylvania Industrial Decarbonization Pathway, by industrial subsector

The key decarbonization pillars employed for this roadmap include energy and material efficiency, electrification, fuel switching, CCS, and production ramp-downs and facility retirements. Across all subsectors, transitioning from fossil fuel combustion to electrification enables roughly half of the total emissions reductions, followed by efficiency, carbon capture, and fuel switching (*see Figure 26*). These levers provide complementary decarbonization benefits and should thus be pursued concurrently for maximum impact.

225 EPA, "Final Rule — Phasedown of Hydrofluorocarbons: Allowance Allocation Methodology for 2024 and Later Years," 2023. https://www.govinfo.gov/content/pkg/FR-2023-07-20/pdf/2023-14312.pdf.

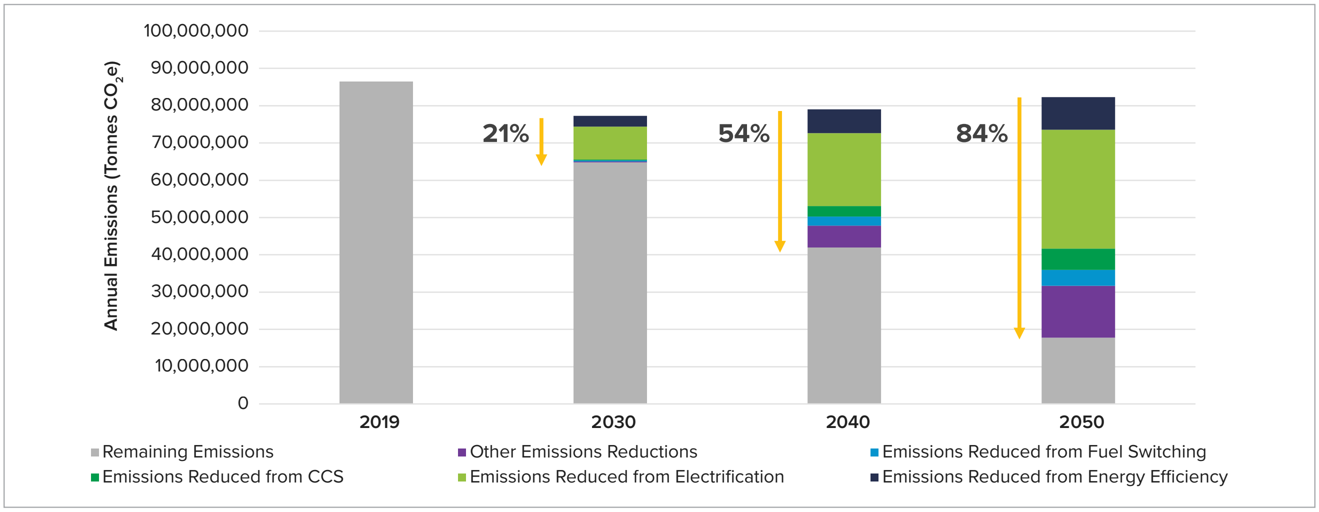


FIGURE 26: Pennsylvania Industrial Decarbonization Pathway, by decarbonization lever

Notably, the effectiveness of electrification in decarbonizing the industrial sector will depend on the rate at which the local and regional electric grid is eventually decarbonized. Additional strategies beyond the levers selected for analysis could potentially have a role in reaching full industrial decarbonization, and these solutions should be further developed and explored, if and when they become more feasible from both technical and financial perspectives.

Across all subsectors, Strategen calculates that the proposed industrial sector decarbonization roadmap will cost approximately $34.6 billion through 2050. Federal 45Q tax credits for CCS projects implemented before 2033 could provide up to $887 million in funding, resulting in a subsidized cost of $33.7 billion. Of the subsectors analyzed, the minerals category (primarily cement and lime production), the iron and steel industry, and oil and gas are estimated to be the most expensive to decarbonize, totaling $16.1 billion in implementation costs.

Industrial Subsector	Pathway Cost ($million)
Oil and Gas Production	$2,900
Underground Coal Mines	$128
Iron and Steel	$3,400
Other Metals	$234
Minerals	$9,800
Chemicals	$183
Refining	$1,300
Glass	$645
Pulp and Paper	$738
Food Processing and Miscellaneous Manufacturing	$640
Other Low Heat Subsectors	$14,600
TOTAL	**$34,600**

TABLE 4: Decarbonization Pathway Cost, by subsector

Of the decarbonization levers considered for this analysis, electrification is expected to account for nearly half of the estimated CO_2e emissions reductions, and likewise comprises the largest share of calculated implementation costs. Given the nascency of CCS and fuel switching to hydrogen, these solutions make up an oversized portion of total implementation costs, relative to their emissions impacts. It should be noted, however, that the allocation of emissions reductions does not necessarily directly correlate with pathway cost and should not be considered an indicator of how state, federal, or private funding should be allocated.

Decarbonization Lever	% of Decarbonization Pathway Abatement Potential	% of Pathway Cost
Energy Efficiency	14%	0%
Electrification	48%	53%
CCS	7%	28%
Fuel Switching	9%	13%
Other[226]	22%	5%

TABLE 5: Breakdown of Cost and Decarbonization Potential, by decarbonization lever

226 This category includes all other actions that do not explicitly fall into the other four levers, including upgrades to oil and gas systems, CMM management, capital costs for hydrogen DRI-EAF in the steel industry, and various raw material substitutions across multiple subsectors.

Impacts and Benefits of this Roadmap

Resource Implications

As shown in the pathways outlined above, fully decarbonizing Pennsylvania's industrial sector will require significant use of clean hydrogen, carbon capture and storage technology, and electrification. Achieving the emissions reductions associated with this roadmap will therefore necessitate increasing clean hydrogen and electricity production, while also expanding infrastructure for the transport and storage of captured carbon and hydrogen.

Clean Hydrogen

In Strategen's decarbonization pathway, clean hydrogen is considered as a central zero-carbon fuel option to provide high-temperature heat for industrial processes. However, as a commodity, hydrogen is in limited supply today, and clean hydrogen is virtually nonexistent. The United States currently produces 10 MMT of hydrogen annually, 95% of which is produced from natural gas via SMR, without any capture or storage of the CO_2 released through the SMR process.[227] This emissions-intensive production process means that nearly all hydrogen currently produced in the United States would not qualify as "clean." However, with federal, state, and private sector efforts, including the Regional Clean Hydrogen Hub program established through the IIJA and production tax credits through the IRA, the production and supply of clean hydrogen is expected to increase significantly in the future. The U.S. National Clean Hydrogen Strategy and Roadmap developed by DOE in partnership with 10 federal agencies, projects that 10 MMT of clean hydrogen will be available annually by 2030 (matching current levels of hydrogen production from unabated natural gas), with 20 MMT produced annually by 2040, and reaching 50 MMT by 2050.[227]

Strategen estimates that the industrial sector pathways outlined for Pennsylvania in this report would require roughly 440,000 MT of hydrogen annually by 2050 if all fuel switching needs were met by hydrogen. This equates to roughly 0.9% of the projected 50 million MT of national clean hydrogen production anticipated in that year.[229]

Industrial Subsector	Annual Clean Hydrogen Demand by 2050 (metric tons)
Oil and Gas Production	0
Underground Coal Mines	0
Iron and Steel	207,890
Other Metals	53,690
Minerals	69,980
Chemicals	5,610
Refining	60,400
Glass	13,230
Pulp and Paper[230]	25,135
Food Processing and Miscellaneous Manufacturing	4,285
Other Low Heat Subsectors	0
TOTAL	440,220

TABLE 6: Annual Demand for Clean Hydrogen in a Decarbonized Pennsylvania Industrial Sector by 2050

227 Office of Energy Efficiency and Renewable Energy (EERE), "Hydrogen Production," DOE, Accessed October 23, 2023. https://www.energy.gov/eere/fuelcells/hydrogen-production; EERE, "Hydrogen Fuel Basics," DOE, Accessed October 23, 2023. https://www.energy.gov/eere/fuelcells/hydrogen-fuel-basics.
228 DOE, National Clean Hydrogen Strategy and Roadmap.
229 Strategen calculated projected demand for hydrogen for industrial uses in Pennsylvania based on the amount of hydrogen required to meet energy needs identified in the developed pathways.
230 Note that the fuel switching needs for pulp and paper are likely to be met at least partially by biomass, which is already used as a fuel in this subsector. As a result, pulp and paper will likely require less than the 25,000 metric tons of clean hydrogen listed in this table.

As mentioned previously, Strategen's analysis does not include a full consideration of hydrogen's lifecycle emissions. Still, it is vital to consider where the commonwealth might access clean hydrogen, as some production sources offer greater climate benefits than others. Producing hydrogen with natural gas, even when coupled with carbon capture, results in much higher life cycle emissions compared with hydrogen produced via electrolysis using either renewable or nuclear electricity (*see Figure 27*).[231] These greater life cycle emissions stem predominantly from the upstream extraction and transport of natural gas, in addition to the reality that CCS cannot capture all of the CO_2 produced during natural gas SMR.[232]

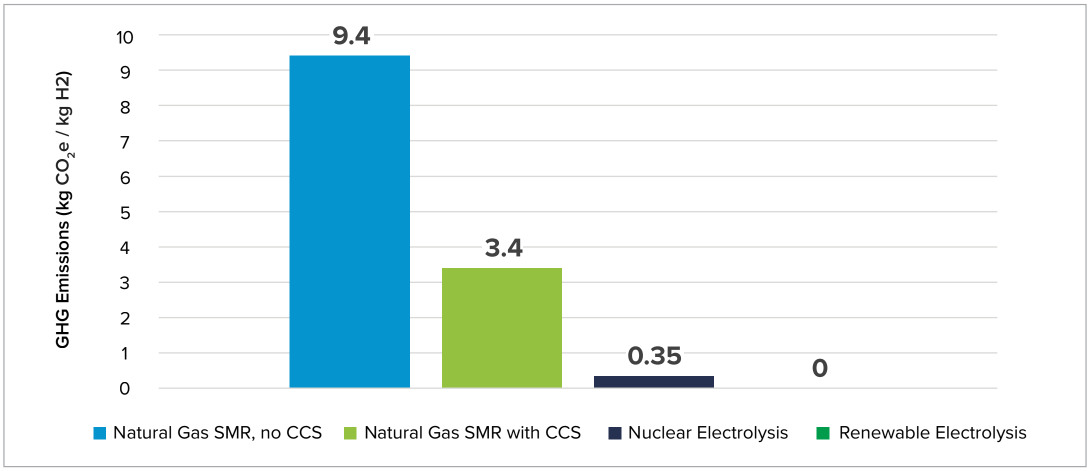


FIGURE 27: Well-to-gate GHG Emissions for Selected Hydrogen Production Pathways | *Source: Elgowainy, A. et al., Hydrogen Life-Cycle Analysis in Support of Clean Hydrogen Production.*

Due to this higher emissions intensity, using natural gas-derived hydrogen for industrial decarbonization may ultimately offset some of the emissions reductions gained through fuel switching. For instance, using hydrogen with a well-to-gate emissions intensity of 4 kg CO_2/kg H2 produced (the upper threshold of DOE's clean hydrogen production standard) to meet all hydrogen needs in this pathway would lead to an additional 1.7 MMT CO_2e left unabated in 2050, relative to using hydrogen produced from renewables through electrolysis, which has near-zero life cycle emissions. In addition, producing hydrogen from natural gas, even if paired with CCS, could further entrench dependency on the fossil fuel industry and require the continued extraction of natural gas in the commonwealth, thereby delaying Pennsylvania's clean energy transition. If all hydrogen used in this industrial decarbonization pathway were produced using natural gas coupled with carbon capture, it would require 81,827 billion BTUs of natural gas, equivalent to roughly 11% of the industrial sector's natural gas consumption in 2020 (when accounting for the additional energy needs of carbon capture).[233] This production process would result in 1.15 MMT of CO_2 being captured with a 96% capture efficiency.

In contrast, using hydrogen produced with zero-emissions electricity carries far greater benefits for the industrial sector in the form of reduced emissions and associated co-benefits. As seen in *Figure 27*, producing hydrogen with nuclear or renewable electricity results in 90-100% lower well-to-gate emissions than production from natural gas paired with CCS. Still, electrolytic hydrogen production introduces new obstacles, namely the need for large quantities of clean power. If all hydrogen produced for this pathway were made using clean electricity from nuclear or renewable sources, it would require 24,470,830 MWh annually, representing roughly 10% of Pennsylvania's total electricity generation in 2021.[234] This roughly translates to adding an additional 8.5 GW of wind to the

231 Elgowainy, A. et al., *Hydrogen Life-Cycle Analysis in Support of Clean Hydrogen Production*, Argonne National Laboratory, 2022. https://publications.anl.gov/anlpubs/2022/10/179090.pdf. Note that this figure averages the well-to-gate emissions of two different types of nuclear electrolysis that are presented separately in this source material.

232 Elgowainy, A., "GREET Model for Hydrogen Lifecycle GHG Emissions: Presentation at H2IQ Webinar," Argonne National Laboratory, June 15, 2022. https://www.energy.gov/sites/default/files/2022-06/hfto-june-h2iqhour-2022-argonne.pdf.

233 Per PA DEP's *Pennsylvania Greenhouse Gas Inventory Report*, Pennsylvania's industrial sector used 737,495 billion BTUs of natural gas in 2020.

234 This electricity demand assumes hydrogen is being produced in a proton exchange membrane (PEM) electrolyzer at a 60% conversion efficiency. Data on Pennsylvania's electricity generation comes from EIA, "Pennsylvania Electricity Profile 2021," November 10, 2022. https://www.eia.gov/electricity/state/Pennsylvania/.

grid every year (at a 33% capacity factor). For comparison, DEP reports that the commonwealth currently has 1.3 GW of total wind capacity.[235] While these figures suggest clear hurdles to hydrogen production at the scale Strategen's pathway requires, analysis indicates Pennsylvania does have the technical potential to produce more than this pathway's required volume of hydrogen exclusively from renewable resources. A high-level analysis by the National Renewable Energy Laboratory estimates that Pennsylvania has the potential for 9.7 MMT of clean hydrogen annually from wind, solar and biomass resources.[236]

In reality, given both announced plans and existing activity in the state thus far, hydrogen used in Pennsylvania's industrial sector is likely to be produced by both natural gas and zero-emissions electricity from renewables and nuclear. Pennsylvania is involved in two successful applications to the IIJA's Regional Clean Hydrogen Hubs program, which are expected to employ both these production methods. The Appalachian Hydrogen Hub, including Pennsylvania, West Virginia, and Ohio, proposes to use natural gas paired with carbon capture, while the Mid-Atlantic Hydrogen Hub, covering southeastern Pennsylvania, Delaware, and New Jersey, will use renewable and nuclear electricity (*Table 9*).[237] Both hubs anticipate that industry will be among their end users, although until more details about specific hub projects and use cases are known, it is difficult to know their exact impact on industrial decarbonization. Publicly available information about the hubs paints a partial picture of Pennsylvania's potential hydrogen supply. The Mid-Atlantic Hydrogen Hub has publicized its intended production volume of 271 metric tons per day by 2032, and Fidelis, one of the ARCH2 partners, has publicized its intent to produce over 500 metric tons per day at a hub-included facility in Mason County, West Virginia.[238] Together, this equates to annual production of about 281,400 metric tons, representing 64% of the annual hydrogen demand estimated in Strategen's pathway by 2050. Importantly, demand from a variety of off takers in Pennsylvania and other states means not all hydrogen produced from the hubs will be available to Pennsylvania industries. Given the limited options for electrification in several industrial subsectors, however, it is widely understood that the industrial sector will be of relatively high priority for hydrogen demand, along with other difficult-to-decarbonize sectors like heavy-duty transportation.[239]

Hub Name	Geographic Region	Anticipated Feedstocks	Anticipated Production	Anticipated Use Cases
Mid-Atlantic Clean Hydrogen Hub (MACH2)[240]	Southeast Pennsylvania, South New Jersey, Delaware	Renewable and nuclear electricity, renewable natural gas	271 metric tons/ day by 2032	Industry (refining), transportation, power
Appalachian Regional Clean Hydrogen Hub[241]	Pennsylvania (Southwest and Northern), Ohio, West Virginia	Natural gas, with carbon capture	Not publicized	Power generation, commercial/ residential buildings, industry, transportation

TABLE 7: Regional Clean Hydrogen Hubs in Pennsylvania

Meeting Strategen's decarbonization pathway would require significantly scaling up clean hydrogen production beyond the production volumes expected through Pennsylvania's two hubs. As the hydrogen sector develops, aided by DOE's hydrogen targets and activities and IRA tax credits, it is likely that additional production facilities will be established both in the commonwealth and in neighboring states. Accordingly, imports from neighboring states may be able to supplement local hydrogen supply. Connecting out-of-state hydrogen production facilities with industrial users would require trucking the fuel to Pennsylvania or building out large-scale hydrogen infrastructure, like long-distance hydrogen pipelines. Both approaches have been considered in different regional hydrogen development planning processes, with trucking a first step to meet early demand as pipeline infrastructure is developed.[242]

235 PA DEP, "Wind Energy," Accessed October 17, 2023. https://www.dep.pa.gov/Business/Energy/Wind/Pages/default.aspx.
236 Milbrandt, A. and Mann, M., *Potential for Hydrogen Production from Key Renewable Resources in the United States*, National Renewable Energy Laboratory, 2007. https://www.nrel.gov/docs/fy07osti/41134.pdf.
237 DOE, Hydrogen Hubs Selections.
238 MACH2, Leading the Way; Fidelis New Energy, "Project Mountaineer GigaSystem," Accessed October 24, 2023. https://fidelisinfra.com/project/mountaineer-gigasystem/.
239 Weiss, T. and Koch Blank, T., "Hydrogen Reality Check: We Need Hydrogen – But Not for Everything," RMI, June 27, 2022. https://rmi.org/we-need-hydrogen-but-not-for-everything/.
240 MACH2, Leading the Way.
241 ARCH2, A Hub for Hydrogen Energy.

As additional information becomes available on specific hydrogen production projects and expected volumes within Pennsylvania and neighboring states, the state's potential to achieve Strategen's decarbonization pathway through clean hydrogen will become clearer. To proactively reduce the risk of competition for limited hydrogen supply, Pennsylvania can prioritize hydrogen use in hard-to-abate sectors such as heavy industry. Early actions by industry and policymakers — such as commitments by industry to produce or use clean hydrogen or enabling policies that channel clean hydrogen toward industrial uses — can help Pennsylvania's industrial sector better access limited hydrogen supply. Engaging the industrial sector in the planning process for Pennsylvania's DOE-awarded hydrogen hubs can be the start of effective hydrogen sector planning and design.

Alternatives to clean hydrogen fuel switching could include the use of biofuels and biomass or the increased use of CCS, all of which come with their own challenges.

Carbon Capture and Sequestration

As with clean hydrogen, carbon capture and sequestration technology is highly limited in usage today, with 30 projects in commercial operation worldwide as of September 2022.[243] The vast majority of operational carbon capture facilities in the United States use the technology for enhanced oil recovery, rather than sequestration.[244] While an increasing number of CCS projects are in development, the industry has had difficulty scaling, and several high-profile projects have been mothballed or completely shuttered for economic reasons.[245] As a result of these challenges, Strategen opted to deploy CCS in instances where emissions would be otherwise unabated after applying other decarbonization levers.

Strategen's proposed decarbonization pathway would result in roughly 5.7 MMT of CO_2 captured from the industrial sector annually by 2050, equivalent to 41.5% of remaining emissions in 2050.

Industrial Subsector	Annual CCS Needs by 2050 (metric tons)
Oil and Gas Production	0
Underground Coal Mines	0
Iron and Steel	1,316,300
Other Metals	0
Minerals	3,655,000
Chemicals	0
Refining	672,000
Glass	70,600
Pulp and Paper[230]	0
Food Processing and Miscellaneous Manufacturing	0
Other Low Heat Subsectors	0
TOTAL	**5,713,900**

TABLE 8: CCS Demand for Industrial Decarbonization in Pennsylvania by 2050, by subsector

242 Trucking and pipelines may be expensive, and pipelines difficult to develop due to siting and cost allocation challenges. Further, interstate transport increases the potential for leakage due to hydrogen's small molecule size. This is an area of ongoing analysis given the interest in hydrogen across the United States and world, with efforts underway to evaluate the potential for leakage and develop prevention measures. For a discussion on hydrogen leakage, see Fan, Z. et al., "Hydrogen Leakage: A Potential Risk for the Hydrogen Economy," Columbia Center on Global Energy Policy, July 5, 2022. https://www.energypolicy.columbia.edu/publications/hydrogen-leakage-potential-risk-hydrogen-economy/. For an example of a regional hydrogen infrastructure analysis, see Lin, J. et al., *HyBuild Los Angeles Phase 2 Report*, Green Hydrogen Coalition, 2023. https://www.ghcoalition.org/ghc-news/hybuild-la-phase-2-report.

243 Zapantis, A. et al., *Global Status of CCS 2022*, Global CCS Institute, 2022. https://status22.globalccsinstitute.com/wp-content/uploads/2022/11/Global-Status-of-CCS-2022_Download.pdf.

244 Jones, A. and Lawson A., *Carbon Capture and Sequestration (CCS) in the United States*, Congressional Research Service, 2022. https://sgp.fas.org/crs/misc/R44902.pdf.

245 Zapantis, A. et al., Global Status of CCS; Swartz, K., "The Kemper Project Just Collapsed. What It Signifies for CCS," E&E News, October 26, 2021. https://www.eenews.net/articles/the-kemper-project-just-collapsed-what-it-signifies-for-ccs/; Volcovici, V., "Carbon Capture Project Back at Texas Coal Plant After 3-Year Shutdown," Reuters, September 14, 2023. https://www.reuters.com/business/energy/carbon-capture-project-back-texas-coal-plant-after-3-year-shutdown-2023-09-14/.

This figure only reflects the CCS required for direct applications in industry and not to produce hydrogen used in industrial processes. If all hydrogen required for this pathway were produced with natural gas coupled with carbon capture, an additional 1.15 MMT of CO_2 would need to be captured and stored (assuming carbon capture at 96% capture efficiency). This would bring the total annual need for carbon storage up to 6.86 MMT of CO_2 per year by 2050.

Pennsylvania's geology could offer a variety of sites for storing captured carbon, including depleted hydrocarbon reservoirs (e.g., oil fields) and saline aquifers. This does not mean, however, that all such formations in the state are suited for carbon sequestration. Multiple DOE reports state that saline aquifers are the likeliest candidates for carbon sequestration.[246] DOE's National Energy Technology Laboratory (NETL) has found that demand for storage of other fuels and fluids (e.g., natural gas, oil, and hydrogen), and the often more economical storage of these products compared to captured carbon, is likely to make the use of depleted hydrocarbon reservoirs and salt caverns uncompetitive for CCS.[247]

Estimates of Pennsylvania's carbon storage potential vary widely. High-end estimates from 2009 suggest Pennsylvania could store up to 83.3 billion metric tons of CO_2 in deep saline formations.[248] More recent studies offer more conservative estimates. *Table 9* summarizes various estimates of Pennsylvania's storage capacity, with focus on saline formations.

Storage Potential Estimate (billion metric tons)	Year Published	Source	Notes
83.3[249]	2009	Geologic Carbon Sequestration Opportunities in Pennsylvania (PA Department of Conservation and Natural Resources)	Predominantly focuses on western Pennsylvania
17.34[250]	2015	Carbon Storage Atlas — Fifth Edition (NETL)	None
1.69[251]	2022	Appalachian Hydrogen Infrastructure Analysis (NETL)	Addresses pressure interference

TABLE 9: Estimates of Pennsylvania's Carbon Storage Potential (saline formations)

It is important to note that the most conservative figure listed above (1.69 billion metric tons) takes into consideration the risk of "pressure interference" among multiple carbon injection projects in a single storage formation. Injecting CO_2 at one site can have the effect of increasing pressures at nearby CO_2 storage sites, which can compromise the safety and integrity of the projects. To avoid this risk, NETL adopted a basin-scale management method that limited the number of projects it assumed could be implemented in the same storage formation at the same time. The resulting figure is a more conservative estimate of Pennsylvania's storage potential, but one that more accurately accounts for the technical and economic limitations associated with carbon sequestration in the state. Given that this estimate is both the most recent of the figures outlined above, and the only one that addresses the risk of pressure interference, this is the CO_2 storage capacity that Strategen assumed for this study.

246 Singh, H. et al., *Appalachian Hydrogen Infrastructure Assessment*, NETL, 2022. https://netl.doe.gov/node/12484. (Hereafter "NETL, Appalachian Hydrogen Assessment"); DOE, Pathways to Commercial Liftoff: Carbon Management.
247 NETL Appalachian Hydrogen Assessment.
248 PA DCNR, *Geologic Carbon Sequestration Opportunities in Pennsylvania*, 2009. http://elibrary.dcnr.pa.gov/GetDocument?docId=1743511&DocName=Geologic-Carbon-Sequestration-Opportunities-in-PA-2009.pdf.
249 This study also estimated storage potential in shales, oil and gas fields, and coal beds. Including these storage sites would bring Pennsylvania's total storage potential up to 88.5 billion metric tons.
250 This study also estimated storage potential in oil and natural gas reservoirs and unmineable coal sites. Including these storage sites would bring Pennsylvania's total storage potential up to 18.95 billion metric tons (the study's "medium estimate").
251 This number was calculated by adding the listed capacities of each storage formation in Pennsylvania included in the Appendix of the NETL study (see Exhibit A-1). Formations with a capacity under 135 MMT did not have precise storage capacity figures listed. Strategen therefore assumed maximum potential capacity in these formations (135 MMT), although it is likely their actual capacity is lower, which would bring the 1.69 billion metric ton estimate down.

Given Pennsylvania's carbon storage capacity of 1.69 billion metric tons and the roughly 5.7 MMT of CO_2 that would need to be sequestered annually by 2050 in Strategen's proposed pathway, achieving the emissions reductions outlined here would require roughly 0.34% of Pennsylvania's total carbon storage capacity annually. Assuming CCS needs remain constant from 2050 onward, Pennsylvania would have capacity to store roughly 294 years of industrial emissions, excluding the potential need for CCS in hydrogen production.

While these figures may suggest plentiful opportunities for sequestration of industrial emissions, the industrial sector is unlikely to be the only user of Pennsylvania's carbon storage capacity. Additional storage needs from the power sector, hydrogen production, and even other states may result in limitations on Pennsylvania's storage resources. In addition, there are several challenges with carbon capture that might make it prudent to maximize other decarbonization levers before relying on CCS. These include the continued struggles in reaching economic viability, a lack of CCS infrastructure at present, and growing local opposition to CCS projects in states across the political spectrum.[252]

As previously explained, carbon utilization is an alternative to sequestration, although utilization was excluded for the purposes of this analysis due both to uncertain utilization opportunities in Pennsylvania and the lesser climate benefits of utilization compared to permanent storage. If carbon utilization were to be pursued in addition to sequestration, corresponding pipeline infrastructure would be required to link capture facilities to the sites that would ultimately use that carbon.

Electricity

A transition away from fuels toward electrification in the industrial sector — coupled with simultaneous electrification in the buildings and transportation sectors — will contribute toward increasing demand for electricity in Pennsylvania. Achieving the emissions reductions from direct electrification of the specific industrial subsectors outlined in this pathway would require an additional 16 Terawatt hours (TWh) of electricity by 2050. Factoring in electrification of heating and cooling of industrial buildings, as well as the other various low heat subsectors, would add another 65 TWh of potential demand for a total of 81 TWh, representing 34% of Pennsylvania's 2022 electric generation. [253]

Industrial Subsector	Annual Electricity Demand by 2050 (MWh)
Oil and Gas Production	225,000
Underground Coal Mines	0
Iron and Steel	4,094,000
Other Metals	982,000
Minerals	0
Chemicals	2,216,000
Refining	369,000
Glass	1,762,000
Pulp and Paper[230]	3,228,000
Food Processing and Miscellaneous Manufacturing	3,349,000
Other Low Heat Subsectors	65,102,000
TOTAL	**81,327,000**

TABLE 10: Annual Electricity Demand in a Decarbonized Pennsylvania Industrial Sector by 2050

252 Howard, K., *Decarbonization: Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage*, U.S. Government Accountability Office, 2022. https://www.gao.gov/products/gao-22-105274; Muller, W., "Louisiana Residents Ask State to Halt Next Phase of Carbon Capture Project," Louisiana Illuminator, August 3, 2023. https://lailluminator.com/2023/08/03/louisiana-residents-ask-state-to-halt-next-phase-of-carbon-capture-project/; Lydersen, K., "Navigator CO_2 Pipeline Is Canceled, But Illinois Opponents Say the Fight Isn't Over," Energy News Network, October 20, 2023. https://energynews.us/2023/10/20/navigator-co2-pipeline-is-canceled-but-illinois-opponents-say-the-fight-isnt-over/?utm_medium=email.

253 Pennsylvania's total electric generation in 2022 was 238.6 TWh, per Advanced Energy United's Insight Engine, which pulls data from the U.S. EIA: https://powersuite.aee.net/portal/states/PA/energy_data.

Electricity demand will be affected not only by direct electrification, but also by clean hydrogen produced through electrolysis, which will require renewable or clean electricity. When considering the electricity required for hydrogen production (assuming all required hydrogen is electrolytic), Pennsylvania's electricity demand increases additionally by roughly 24 TWh annually, for a total of about 105 TWh.

As mentioned previously, the GHG emissions reductions possible from electrification and electrolytic hydrogen usage ultimately depend on the emissions from power sector sources. This means that not only will Pennsylvania have to produce more electricity to meet its decarbonization goals across industry and other sectors, but it will also have to do so *more cleanly*. Fully decarbonizing the power sector, while expanding it to meet growing demand from industry, buildings, and transportation, will require a significant increase in the generation and storage of clean energy, while maintaining existing nuclear and hydropower capacity. An expansion in associated electric system infrastructure, (e.g. transmission), will likely need to accompany this generation buildout to link renewable electricity production with demand hubs, but more research is necessary to understand the full scale and resulting costs of these improvements.

Equity and Environmental Justice

The industrial sector in Pennsylvania is not only a significant contributor to GHG emissions, but also a major source of other air, water, and soil pollutants that have detrimental effects on communities' health. Major air pollutants from industrial sites include particulate matter (PM10 and PM2.5), sulfur dioxide, lead, nitrogen oxides (NO_x), heavy metals, and chemical compounds.[254] Sustained exposure to these pollutants can result in higher rates of premature death, cancer, chronic respiratory conditions, cardiovascular disease, and other health issues.[255]

Unfortunately, the health impacts of industrial pollution are not equally shared, both across the country and in Pennsylvania specifically. Nationally, roughly 46% of all industrial facilities are located in federally designated disadvantaged communities (as determined by numerous environmental, health, and economic indicators), despite these communities comprising only 36% of all census tracts.[256] In Pennsylvania, seven of the ten largest greenhouse gas emitting industrial sites are located in areas identified by the Pennsylvania DEP as environmental justice areas, despite these areas making up only 20% of the census block groups in the state.[257]

The industrial decarbonization pathway proposed in this report would mark a significant step toward reducing environmental injustices in Pennsylvania, by limiting many of the disproportionate impacts that industrial pollution has on communities across the commonwealth. While detailed geospatial analysis would be required to accurately quantify the benefits of reducing local air pollutants, based on the exact proximity of industrial facilities to local populations, the use of energy efficiency, electrification, and fuel switching solutions in Strategen's roadmap is expected to result in large reductions in the emission of criteria pollutants from unabated fossil fuel combustion in industrial sector operations.

254 American Lung Association, "Commercial and Industrial," Last modified November 17, 2022. https://www.lung.org/clean-air/outdoors/what-makes-air-unhealthy/commercial-and-industrial.

255 Fos, P. et al., *Health Status in Fence-Line Communities: The Impact of Air Pollution*, International Journal of Family Medicine and Primary Care, 2021. https://sph.lsuhsc.edu/wp-content/uploads/2021/10/Fenceline-communities-and-AIr-Pollution.pdf; Terrell, K. and St Julien, G., *Air Pollution Is Linked to Higher Cancer Rates Among Black or Impoverished Communities in Louisiana*, Environmental Research Letters, 2022. https://doi.org/10.1088/1748-9326/ac4360; EPA, "Air Pollution and Cardiovascular Disease Basics," Last modified August 23, 2023. https://www.epa.gov/air-research/air-pollution-and-cardiovascular-disease-basics; Mock, K. et al., *Breathing Room: Industrial Zoning and Asthma Incidence Using School District Health Records in the City of Santa Ana, California*, International Journal of Environmental Research and Public Health, April 2022. https://doi.org/10.3390/ijerph19084820.

256 DOE Pathways to Commercial Liftoff: Industrial Decarbonization.

257 These figures are based on Strategen's analysis of the highest-emitting industrial facilities (including underground coal mines) reporting to the GHGRP, which were identified at https://www.epa.gov/ghgreporting/ghgrp-state-and-tribal-fact-sheet. The addresses of the top 10 facilities were then searched in PA DEP's PennEnviroScreen tool to identify those in EJ areas: https://gis.dep.pa.gov/PennEnviroScreen/. The percentage of census block groups that are identified as EJ areas was calculated by analyzing raw EJ area data from https://newdata-padep-1.opendata.arcgis.com/datasets/PADEP-1::environmental-justice-areas-pennenviroscreen-2023/about.

Still, there are additional equity and justice implications associated with specific decarbonization levers analyzed in this pathway, which should be considered in decarbonization planning:

+ **Carbon Capture and Sequestration**: Community concern about the impacts of carbon capture and sequestration has resulted in pushback against CCS projects across the country.[258] Some communities worry that carbon capture could perpetuate fossil fuel extraction (specifically fracking) and usage, which raises both environmental and economic concerns, given that natural gas extraction has thus far failed to provide substantial job creation for the region, and continuation or expansion may not lead to proportional economic growth.[259] In addition, there are also concerns about the land use required for carbon pipelines and the safety and monitoring necessary for carbon transport and permanent sequestration. Fenceline communities that have been overburdened by industrial pollution have also raised important questions about how CCS may impact local air quality.[260] Research on this point is limited and has seemingly yielded mixed results. In some cases, the need to isolate CO_2 in an emissions stream for effective capture can result in non-CO_2 pollutants being filtered out, which may improve local air quality.[261] On the other hand, the additional energy needed to operate CCS equipment (referred to as the "energy penalty") may partially offset these potential air quality gains if that energy is derived from fossil fuels[262] The impacts of CCS on local air quality warrant further study, especially in industrial applications.
+ **Clean Hydrogen**: Equity and justice impacts of clean hydrogen pertain both to its production and its ultimate combustion at industrial sites. On the production side, community concern has been heaviest with natural gas-derived hydrogen, which — even if coupled with carbon capture — would result in the same upstream environmental and health impacts associated with natural gas extraction and transport, as well as air pollution impacts from steam methane reforming (if not abated).[263] Concerns with hydrogen combustion apply to all hydrogen types, regardless of production pathway. While hydrogen does not release GHG emissions when combusted, it does produce NO_x, a class of criteria air pollutant, that can offset some of the air quality benefits associated with fuel switching from fossil fuels to hydrogen. This challenge, and strategies to address it, are discussed further below.
+ **Biomass**: While biomass energy, made from agriculture, forestry, or other waste feedstocks, is often portrayed as "carbon neutral," the associated carbon benefits are complicated. The environmental benefits of biomass largely depend on the feedstock being used, the inputs required to grow and harvest that feedstock, and whether land conversion was required to produce that feedstock.[264] There are also health implications from burning biomass, regardless of the feedstock used to create it.[265] A 2022 study indicated that, in Pennsylvania, the use of biomass in industrial boilers creates the greatest public health burden from PM2.5 of any combusted fuel, higher even than coal and natural gas.[266]
+ **Electrification**: While electrification will have positive air quality impacts at industrial sites themselves by replacing direct fossil fuel combustion, it may lead to equity or justice concerns in the power sector. The industrial sector's increasing power demand would in turn require additional electricity generation, which

258 Haiar, J., "Unusual Alliances Emerge Amid Opposition to Eminent Domain for Carbon Pipelines," South Dakota Searchlight, July 7, 2023. https://southdakotasearchlight.com/2023/07/07/unusual-alliances-emerge-amid-opposition-to-eminent-domain-for-carbon-pipelines/; Muller, W., "Louisiana Residents Ask State to Halt Next Phase of Carbon Capture Project," Louisiana Illuminator, August 3, 2023. https://lailluminator.com/2023/08/03/louisiana-residents-ask-state-to-halt-next-phase-of-carbon-capture-project/.

259 O'Leary, S. et al., *Destined to Fail: Why the Appalachian Natural Gas Boom Failed to Deliver Jobs & Prosperity and What It Teaches Us*, Ohio River Valley Institute, 2021. https://ohiorivervalleyinstitute.org/wp-content/uploads/2021/07/Destined-to-Fail-FINAL.pdf.

260 Cilento, C., *Decarbonizing Louisiana's Industrial Sector: The Importance of Community-Centric Approaches, Center for Climate and Energy Solutions*, 2023. https://www.c2es.org/document/decarbonizing-louisianas-industrial-sector-the-importance-of-community-centric-approaches/.

261 Koornneef, J. et al., "Carbon Dioxide Capture and Air Quality," in *Chemistry, Emission Control, Radioactive Pollution, and Indoor Air Quality*, July 2011. https://doi.org/10.5772/18075.

262 European Environment Agency, "Carbon Capture and Storage Could Also Impact Air Pollution," November 17, 2011. https://www.eea.europa.eu/highlights/carbon-capture-and-storage-could.

263 Sun, P. et al., *Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities*, Environmental Science & Technology, April 2019. https://doi.org/10.1021/acs.est.8b06197.

264 EIA, *Monthly Energy Review October 2023: Environment*, 2023. https://www.eia.gov/totalenergy/data/monthly/pdf/sec11_n.pdf.

265 EIA, "Biomass Explained: Biomass and the Environment," Last modified November 7, 2022. https://www.eia.gov/energyexplained/biomass/biomass-and-the-environment.php.

266 Buonocore, J. et al., *A Decade of the U.S. Energy Mix Transitioning Away from Coal: Historical Reconstruction of the Reductions in the Public Health Burden of Energy*, Environmental Research Letters, May 2021. https://doi.org/10.1088/1748-9326/abe74c.

may inadvertently result in the expansion of natural gas extraction and use in power plants if efforts are not made to make that power renewable. Even in the case of renewable power generation, land use requirements for solar and wind may have negative community impacts if not planned inclusively. In addition to increasing power production, the need to transport that power to industrial sites would necessitate the buildout of additional power infrastructure like transmission lines and substations, which would again have land use implications.

Nitrogen Oxides (NO_x) from Hydrogen Combustion

Although Strategen's developed industrial decarbonization pathway will lead to sharp decreases in many criteria pollutants by reducing the use of fossil fuels, combustion of hydrogen, which is proposed for several applications in this roadmap, would also result in the release of NO_x, which carries air quality implications. These toxic compounds are released from burning fuel at high temperatures, for example in automobiles, power plants, industrial boilers, and cement kilns, and they contribute to the presence of ground-level ozone.[267]

While the linkage between hydrogen combustion and NO_x emissions is well established, research varies widely on the severity of NO_x emissions that can arise from burning hydrogen. Some sources suggest that hydrogen's NO_x emissions can be significantly higher than those released from natural gas combustion, while others estimate lower total NO_x production.[268] Much of the research into hydrogen's NO_x emissions seems to focus on blends of hydrogen and natural gas and on hydrogen applications in the heating and transportation sectors. More research is needed to fully understand the NO_x implications of high-temperature, pure hydrogen combustion at industrial sites.

There are several ways that NO_x emissions from hydrogen combustion can be reduced. These include lowering hydrogen's flame temperature, limiting the flame's exposure to nitrogen in the air, and treating exhaust gases to remove NO_x post combustion.[269] Experts suggest that these, and other, innovations can result in NO_x emissions comparable to, or lower than, those released from the combustion of natural gas in some applications (e.g., turbines).[270] It is important to note, however, that strategies to reduce NO_x emissions in turbine applications may not carry over to many industrial purposes because the need for higher levels of heat may make lowering the flame temperature infeasible. Additional research, development, and demonstration projects can help identify NO_x control measures relevant for industrial hydrogen applications. Policy solutions, like hydrogen-specific emissions standards, are also needed to drive progress toward the lowest NO_x emissions possible, ideally below the levels of current natural gas combustion.

Social Benefits of Reduced Greenhouse Gas Emissions

Given the negative health, environmental, and economic impacts associated with climate change, it is important to assess the impacts of reducing GHG emissions not only in costs incurred, but also in broad societal benefits created. The "social cost of carbon" (SCC) is one method for doing so. The SCC quantifies the societal cost of emitting each additional metric ton of carbon, including human health impacts, agricultural impacts, property damage from natural disasters, disruption of energy services, and other economic and environmental costs.[271] The current interim federal SCC stands at $51/metric ton, although in late 2022, the EPA proposed increasing

267 EPA, "Nitrogen Oxides (NO_x) Control Regulations," Accessed October 23, 2023. https://www3.epa.gov/region1/airquality/nox.html.

268 Wright, M. and Lewis, A., *Emissions of NOx from Blending of Hydrogen and Natural Gas in Space Heating Boilers*, Elementa: Science of the Anthropocene, May 2022. https://doi.org/10.1525/elementa.2021.00114.

269 Lewis, A., *Optimizing Air Quality Co-Benefits in a Hydrogen Economy: A Case for Hydrogen-Specific Standards for NO_x Emissions*, Environmental Science: Atmospheres, June 2021. https://doi.org/10.1039/d1ea00037c.

270 Dennis, R. and McDonell, V., "H2IQ Hour: Addressing NOx Emissions from Gas Turbines Fueled with Hydrogen," NETL and UC Irvine Combustion Laboratory, September 15, 2022. https://www.energy.gov/eere/fuelcells/h2iq-hour-addressing-nox-emissions-gas-turbines-fueled-hydrogen.

271 Interagency Working Group on the Social Cost of Greenhouse Gases, *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide — Interim Estimates Under Executive Order 13990*, 2021. https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf.

272 EPA, *EPA External Review Draft of Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*, 2022. https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf. (see Table 4.2.1 for Strategen's selected SCC).

that value significantly.[272] Strategen employed these updated estimates, assuming a 2.5% discount rate, for its SCC analysis. By 2050, EPA's SCC will increase to $205/metric ton, meaning every metric ton of CO_2e emitted in that year creates $205 in societal damages. Applying the SCC to the business-as-usual emissions that Strategen estimates in 2050 indicates that failing to decarbonize Pennsylvania's industrial sector would result in $16.88 billion in damages in 2050 alone. In contrast, Strategen's decarbonization pathway would reduce 2050 emissions by 68.6 MMT, avoiding annual damages valued at just over $14 billion by 2050.

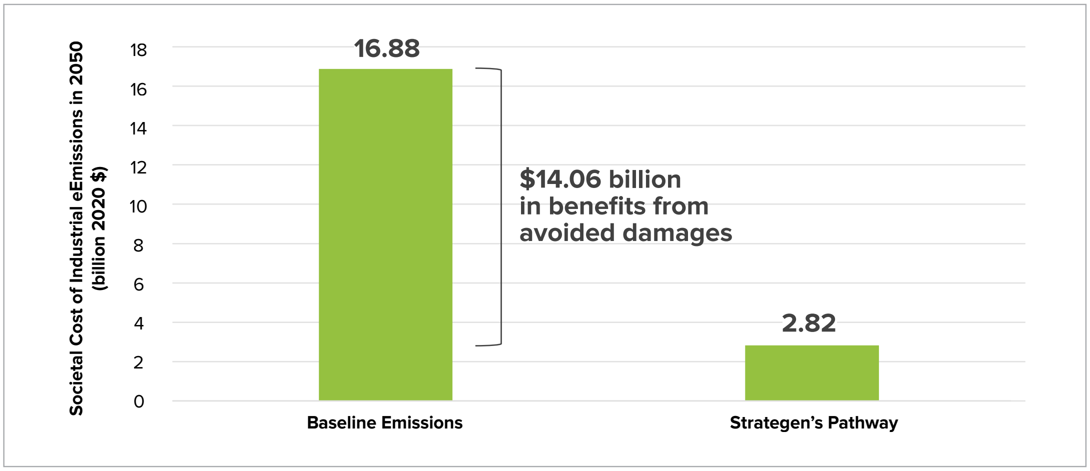


FIGURE 28: Societal Benefits of Reduced GHG Emissions as a Result of Strategen's Pathway, 2050

Economy and Jobs

Given the significant role that these industries play in Pennsylvania's economy, the decarbonization of the industrial sector will certainly have economic impacts across the commonwealth. These impacts will vary across subsectors and geographies. In some cases, such as coal mining and the oil and gas industry, demand and production declines will result in job losses, while in others, production increases and the need for localized decarbonization retrofits are likely to result in job creation and other local economic benefits.

National-level analysis from DOE suggests that industrial decarbonization efforts will create millions of direct and indirect job-years (i.e., one job for one year),[273] translating to hundreds of thousands of jobs. Skilled trade professions — an area in which Pennsylvania has a robust workforce — are likely to see the largest gains. A significant portion of direct jobs created by decarbonizing the chemicals and refining subsectors, for instance, will go to trade workers such as welders, electricians, metal workers, and others.[274] Across all industrial subsectors, the scale-up required in energy efficiency, renewable energy generation, and associated infrastructure for electrification, hydrogen, and other purposes are all likely to result in job growth.

Industrial energy efficiency is particularly likely to have a strong, locally rooted economic impact in Pennsylvania. Energy efficiency is already the largest segment of Pennsylvania's clean energy economy by far, employing the greatest number of workers and seeing consistent job growth year over year.[275] Prioritization of industrial efficiency efforts, as assumed in this pathway, would be expected to result in large local economic benefits, given that many efficiency improvements, such as retrofits or other equipment installations, are often performed by local workers, who in turn spend income in the local economy. Previous analysis conducted by Strategen focused on southwestern

272 EPA, *EPA External Review Draft of Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*, 2022. https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf. (see Table 4.2.1 for Strategen's selected SCC).
273 DOE, Pathways to Commercial Liftoff: Decarbonizing Chemicals and Refining.
274 Ibid.
275 BW Research Partnership, *2022 Pennsylvania Clean Energy Employment Report*, PA DEP, 2022. https://files.dep.state.pa.us/Energy/Office%20of%20Energy%20and%20Technology/OETDPortalFiles/2022_Energy_Report/2022_PA_CEER_3.4vw.pdf. (Hereafter "PA DEP, Clean Energy Employment Report"); BW Research Partnership, *United States Energy & Employment Report 2023: Energy Employment by State*, DOE, 2023. https://www.energy.gov/sites/default/files/2023-06/2023%20USEER%20States%20Complete.pdf.

Pennsylvania found that energy efficiency investments yield greater local economic returns than fossil fuel extraction or power generation, both due to more jobs being created and higher wages in those jobs.[276]

Conversely, jobs associated with fossil fuel extraction and delivery, and to a smaller extent petrochemicals, are likely to decline as a result of the production ramp-downs and facility retirements included in this pathway. These shifts can have negative local economic impacts if intentional effort is not made to channel these workers' skills toward other industries. Retraining and job placement programs can help, particularly for roles in which existing skillsets may overlap with future needs, such as pipefitting and boiler making. Workforce development can remain a challenge, however, where there are geographic mismatches in job and labor availability, and in attracting legacy workers to new job opportunities. PA DEP's *Clean Energy Employment Report* noted that many union members in energy-connected work view the clean energy transition negatively and don't see it as a promising alternative to existing jobs.[277] Fortunately, the report also found that unions are interested in opportunities for skills transfer in select technologies, including energy efficiency, carbon capture, and hydrogen, offering promise that these technologies can provide logical applications for existing workers to leverage their expertise.[278]

While it is clear that decarbonizing the subsectors outlined in this report has the potential to create quality jobs, detailed economic impact analysis is necessary to determine the net economic impact of this decarbonization pathway in Pennsylvania, including a full assessment of implications for jobs, wages, local revenue, and other economic indicators.

Pennsylvania's Industrial Competitiveness

While the local economic impacts of this pathway warrant further study, there is a clear competitiveness advantage that Pennsylvania could gain by proactively pursuing industrial decarbonization. Government efforts internationally, federally, and at the state level are driving demand for low-carbon industrial products, with implications for the way Pennsylvania's industrial companies compete in the market. The federal government has been leveraging its status as the world's largest direct purchaser to drive demand for low-carbon industrial goods through its Buy Clean initiative.[279] In September 2022, the Biden Administration announced that the federal government would prioritize purchasing steel, concrete, asphalt, and flat glass produced with lower emissions, and it intends to expand the list of covered products in the future.[280] Already, federal projects that apply these new preferred procurement standards have launched.[281] Multiple states, including neighboring New York, New Jersey, and Maryland, are duplicating these efforts to prioritize low-carbon product purchases.[282]

Internationally, as well, there is a growing link between emissions reductions and trade competitiveness. The European Union's (EU) Carbon Border Adjustment Mechanism (CBAM) is a prime example. The mechanism will apply a carbon tax to heavily traded industrial goods entering the EU beginning in 2026, including iron, steel, cement, and fertilizers.[283] Products with higher emissions will face higher tax penalties. Other countries, including the United Kingdom and Canada, have considered implementing similar policies. Pennsylvania can prepare for these anticipated national and global market shifts by making proactive investments in industrial decarbonization today.[284]

276 Goodenbery, J. et al., A Clean Energy Pathway.
277 PA DEP, Clean Energy Employment Report.
278 Ibid.
279 Federal Buy Clean Initiative.
280 The White House, "FACT SHEET: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century," September 15, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-buy-clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/.
281 The White House, "FACT SHEET: Biden-Harris Administration Advances Cleaner Industrial Sector to Boost American Manufacturing and Cut Emissions," March 8, 2023. https://www.whitehouse.gov/briefing-room/statements-releases/2023/03/08/fact-sheet-biden-%E2%81%A0harris-administration-advances-cleaner-industrial-sector-to-boost-american-manufacturing-and-cut-emissions/. (Hereafter "The White House, Cleaner Industrial Sector").
282 Ibid; Colorado Office of the State Architect, "Buy Clean Colorado Act," Last modified July 2022. https://osa.colorado.gov/energy-environment/buy-clean-colorado-act. (Hereafter "Buy Clean Colorado"); California Department of General Services, "Buy Clean California Act," Last modified September 29, 2023. https://www.dgs.ca.gov/PD/Resources/Page-Content/Procurement-Division-Resources-List-Folder/Buy-Clean-California-Act. (Hereafter "Buy Clean California").
283 Benaim, E., "What American Manufacturers Need to Know About the European Union's Carbon Border Adjustment Mechanism," Third Way, October 2, 2023. https://www.thirdway.org/memo/what-american-manufacturers-need-to-know-about-the-european-unions-carbon-border-adjustment-mechanism#.
284 Leith, D. et al., "UK Government Launches Consultation on a Carbon Border Adjustment Mechanism and Other Measures," EY, March 30, 2023. https://www.ey.com/en_gl/tax-alerts/uk-government-launches-consultation-on-a-carbon-border-adjustmen; Department of Finance Canada, "Exploring Border Carbon Adjustments for Canada," Last modified June 2, 2023. https://www.canada.ca/en/department-finance/programs/consultations/2021/border-carbon-adjustments/exploring-border-carbon-adjustments-canada.html.

Maximizing the Local Benefits of Industrial Decarbonization

As previously discussed, industrial decarbonization has strong potential to bring economic, health, and equity benefits to communities across Pennsylvania. It shouldn't be assumed, however, that all of these benefits will necessarily come to fruition. Intentional efforts must be made — both by state government and the private sector — to engage communities and workers in the industrial transition in order to maximize benefits. Early and frequent community engagement should seek to understand communities' existing challenges, solicit their concerns about a potential project, and find strategies to address these concerns (e.g., installing scrubbers at an industrial facility to capture criteria pollutants).

Deliberate efforts to involve and develop local workforces in industrial decarbonization are paramount in creating economic benefits for Pennsylvania. Creating and supporting existing career "pipeline" programs, pre-apprenticeships, apprenticeships, and on-the-job training programs for high school and college students can channel new workers to key industries. Training, upskilling, and job placement programs for existing industrial workers will also be necessary to offset job losses that will result from decarbonization, predominantly in fossil fuel extraction subsectors. Pennsylvania's robust workforce development system, including its trade unions and community colleges, will be a vital partner in these efforts. Lastly, effective workforce engagement should ideally extend beyond job creation and placement. Ensuring that jobs offer family sustaining wages and safe working conditions will be key to both attracting and retaining talent.

The emphasis on benefits sharing from decarbonization projects has increased notably due to recent federal efforts. In implementing funding from the IIJA, DOE has required funding applicants to submit community benefits plans (CBP) that outline a project's approach to engaging communities and labor, investing in America's workforce, and promoting equity and justice. The CBP contributes 20% of an applicant's score in the application merit review, which in many cases may be enough to make or break a potential project. Industrial companies seeking funding through DOE programs should familiarize themselves with these CBP requirements and prioritize effective community benefits planning as a key to attaining and successfully implementing federal funding.

Regardless of whether a project is receiving federal funding, investing in authentic community engagement and benefits planning from the start is a vital component in lasting project success and long-term economic health. Such efforts can result in increased project support, accelerated progress, and greater prosperity for communities across the commonwealth.

Complementary Actions for Industrial Decarbonization

Achieving the emissions reductions outlined in this report necessitates strong action by both the public and private sectors. The following enabling actions for both industry and state government can serve to drive forward industrial decarbonization in the commonwealth, while ensuring communities benefit and Pennsylvania maintains its strong economy.

Advancing Decarbonization:

+ **Maximize energy efficiency investments in industry to minimize the need for more costly decarbonization solutions**: As discussed previously, energy efficiency investments are often a natural first step in decarbonization efforts and can reduce the need for more costly solutions, such as electrification, fuel switching, or carbon capture, which often have higher capital costs and longer returns on investment or may depend on federal incentives to be cost effective at all. In addition, while other decarbonization solutions may require further technological development or longer implementation periods, energy efficiency is often "shovel ready." Pennsylvania has a strong history in the energy efficiency sector and is already actively working with industrial companies on efficiency efforts, for instance through its Industrial Resource Centers. Increasing state funding and staffing for industrial efficiency measures, including through site assessments and technical assistance, can help companies save money while incentivizing early emissions reductions.
+ **Accelerate the decarbonization of Pennsylvania's power sector to enable economy-wide emissions reductions**: The power sector will be a critical driver of Pennsylvania's economy-wide decarbonization as industry, transportation, and buildings electrify. Expanding the role for clean and renewable energy in Pennsylvania's traditionally fossil-heavy grid is essential for electrification to result in meaningful emissions reductions. Updating and expanding the Alternative Energy Portfolio Standard, for which targets have already been met, offers a natural venue to accelerate power sector decarbonization in Pennsylvania, while bringing the state in line with its neighbors, many of whom have ambitious clean electricity standards that drive private sector renewable investments.[285]
+ **Explore options for an economy-wide carbon pricing mechanism, drawing on examples from other states**: Although a carbon price may be introduced in Pennsylvania via RGGI, the commonwealth's participation remains uncertain and the program only applies to power sector emissions.[286] To strengthen incentives for decarbonization in the industrial sector, Pennsylvania should explore options for economy-wide carbon pricing. California and Washington state have both implemented market-based "cap-and-trade" and "cap-and-invest" programs, respectively, to advance those states toward their climate goals.[287] New York is also in the early stages of creating a cap-and-invest program.[288] Pennsylvania could potentially coordinate with neighboring states, including New York, and key impacted stakeholders throughout the commonwealth, to assess possibilities for a similar program. Collaboration across a variety of parties, including Pennsylvania's legislature, executive branch, industry, labor unions, local communities, and others throughout these efforts would also ensure a comprehensive examination incorporating a full range of perspectives.

285 Cilento, C., *Manufacturing a Decarbonized Future in Southwestern Pennsylvania*, Center for Climate and Energy Solutions, 2023. https://www.c2es.org/document/manufacturing-a-decarbonized-future-in-southwestern-pennsylvania/.

286 Huangpu, K. and Meyer, K., "Gov. Josh Shapiro Appeals Decisions that Struck Down Key climate Program to Pa.'s Highest Court," Spotlight PA, November 21, 2023. https://www.spotlightpa.org/news/2023/11/pennsylvania-josh-shapiro-climate-change-appeal-regional-greenhouse-gas-initiative-court-case/.

287 California Air Resources Board, "Cap-and-Trade Program," Accessed October 27, 2023. https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program; Washington State Department of Ecology, "Washington's Cap-and-Invest Program," Accessed October 27, 2023. https://ecology.wa.gov/Air-Climate/Climate-Commitment-Act/Cap-and-invest.

288 New York State, "Cap-and-Invest," Accessed October 27, 2023. https://capandinvest.ny.gov/.

Strategic Planning and Funding:

- **Continue to detail plans to decarbonize Pennsylvania's industrial sector in the next Climate Action Plan (CAP) based on lessons learned from other states**: Successful industrial decarbonization requires effective planning, making Pennsylvania's CAP a key precursor to progress. In the next CAP, the state should explore a greater array of options for industrial decarbonization, while maintaining emphasis on industrial efficiency, as was done in the 2021 CAP. Other states' climate plans can serve as models for Pennsylvania in this effort. Louisiana's CAP, for instance, includes 13 distinct strategies to accelerate emissions reductions in the state's large industrial sector.[289]
- **Evaluate and take advantage of federal funding opportunities and incentives**: The IIJA and IRA made available a wealth of federal funding to advance industrial decarbonization, of which both Pennsylvania state agencies and the private sector should seek to take advantage. As outlined previously, these opportunities include a range of tax credits to support decarbonization retrofits at industrial facilities, loans for emerging industrial decarbonization technologies, and grants for decarbonization research and demonstrations. These opportunities can jumpstart the development and demonstration of clean energy technologies in Pennsylvania to help them become independently cost effective and sustainable at scale. While some program application windows have closed, Pennsylvania state agencies and industrial companies should catalog remaining funding opportunities and identify high-priority programs that can support decarbonization efforts.

Community and Economic Benefits:

- **Pursue community and worker engagement and benefits planning for decarbonization projects and policies**: Given the industrial sector's large economic footprint in Pennsylvania, coupled with its environmental and health impact on communities across the commonwealth, meaningful engagement with workers and communities will be essential to planning for industrial decarbonization in a way that benefits these groups. State agencies and companies pursuing decarbonization projects should proactively engage with these stakeholders in the project planning phase to hear their potential concerns about projects (e.g., job or pollution impacts), and then pursue efforts to address these concerns, for example through community benefits plans. Emphasis should be placed on communities that have been overburdened by industrial activity or otherwise marginalized. Using mapping tools like the recently updated PennEnviroScreen Tool can help state agencies and companies understand the demographics of communities with which they are engaging and tailor their outreach accordingly, for instance by enhancing public participation efforts in environmental justice areas, as outlined in DEP's revised Environmental Justice Policy.[290] While this policy is intended for DEP activities, it offers best practices applicable to other state agencies and the private sector as well.
- **Invest in training and job placement programs that can channel existing workers' skills to growth industries**: Industrial decarbonization will necessarily result in job creation in some subsectors and job losses in others, especially fossil fuel extraction and delivery. To reduce the negative economic impacts, Pennsylvania should invest in training, upskilling, and job placement programs to leverage these workers' expertise in growth industries. Hydrogen and carbon capture are particularly ripe for the transfer of skills from existing fossil workers. In implementing these programs, government agencies and the private sector should ensure training and new job opportunities are geographically accessible to existing workers and that they can attract talent with competitive wages and benefits.

289 Climate Initiatives Task Force, *Louisiana Climate Action Plan*, 2022. https://gov.louisiana.gov/assets/docs/CCI-Task-force/CAP/Climate_Action_Plan_FINAL_3.pdf.
290 PA DEP, "Environmental Justice Policy Revision," Accessed October 23, 2023. https://www.dep.pa.gov/PublicParticipation/OfficeofEnvironmentalJustice/Pages/Policy-Revision.aspx.

+ **Explore options for state procurement of low-carbon industrial products to foster demand and in-state economic growth**: Government procurement can be a powerful demand driver for low-carbon goods, helping companies who make the investment to decarbonize their industrial processes become more competitive in the marketplace. The European Union, federal government, and neighboring states have all taken steps to align their procurement with decarbonization goals. Maryland, New Jersey, and New York are participating in the Federal-State Buy Clean Partnership, which prioritizes procurement of lower-carbon infrastructure materials (e.g., steel, concrete) in state-funded projects.[291] Pennsylvania could join this initiative or create its own Buy Clean program, as Colorado and California have done. Such a step can open up new markets for low-carbon goods in the state and make Pennsylvania companies more competitive in these markets, resulting in local economic benefits.[292]

291 The White House, Cleaner Industrial Sector.
292 Buy Clean Colorado; Buy Clean California.

Conclusion

As a state with a strong history of industrial production, particularly in heavy-emitting industries, Pennsylvania faces a challenging road to full decarbonization. Strategen's pathway demonstrates that, with proactive measures such as those outlined in this report, Pennsylvania can reduce industrial emissions from 2019 levels by 21% by 2030 and 84% by 2050, offering significant contributions to both state and national emissions reduction targets. Electrification is anticipated to play the greatest role in the sector's decarbonization, aided by the eventual decarbonization of the power sector.

Achieving these emissions reductions would cost $34.6 billion through 2050, but would also avoid just over $14 billion in environmental, health, and economic costs in 2050 alone, compared with a business-as-usual scenario. Industrial decarbonization would also deliver other benefits throughout the commonwealth, including equity improvements by reducing the disproportionate impacts of industrial pollution on disadvantaged communities, local economic growth through the need for facility retrofits and the expansion of new industries, and strengthened long-term competitiveness in national and global economies increasingly driven towards markets that value sustainability and environmental attributes. While decarbonization will necessarily involve production and employment shifts across industrial subsectors, proactively preparing for these shifts and embracing the opportunities that come with thoughtful and informed industrial decarbonization planning can position Pennsylvania to play a critical role in the transition to a zero-carbon future.

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